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RANKING TREATMENT OPPORTUNITIES IN EXISTING TIMBER STANDS ON WHITE PINE LAND IN THE NORTHERN REGION

by

J. H. Wikstrom and Jack R. Alley

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah

This is one of a series of reports published by the Intermountain Forest and Range Experiment Station. These reports are the result of a study initiated in 1962 to evaluate management alternatives on lands capable of growing white pine within National Forests in eastern Washington, northern Idaho, and western Montana. The work was done in cooperation with the Northern Region of the U.S. Forest Service. The following reports are included in the series:

Relations between western white pine site index and tree height of several associated species, by Glenn H. Deitschman and Alan W. Green. U.S. Forest Service Research Paper INT-22, 1965.

Market trends for western white pine, by Robert E. Benson and Larry L. Kirkwold. U.S. Forest Service Research Note INT-65, 1967.

Cost control in timber growing on the National Forests of the Northern Region, by J. H. Wikstrom and J. R. Alley. U.S. Forest Service Research Paper INT-42, 1967.

Evaluating species alternatives for National Forest land capable of growing western white pine, by Alan W. Green and Jack R. Alley. U.S. Forest Service Research Paper INT-43, 1967.

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Jack R. Alley is Chief of the Branch of Timber Management Planning in the Forest Service Regional Office in Missoula, Montana. A 1940 graduate of the University of Idaho, he joined the Forest Service in 1946. His career has included assignments as assistant ranger and district ranger on the Colville, Flathead, Nezperce, and Clearwater National Forests. In 1958 he joined the valuation section of the Timber Management Branch in Missoula, and he later served the Regional Office in Ogden in a similar capacity. Until 1966 he was a special cooperator with the Intermountain Forest and Range Experiment Station in a study of the management of white pine lands in the Northern Rocky Mountains.

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FOREWORD

A forest typically is made up of a large number of stands differing in stage of development, composition, and condition, and often intermingled with nonstocked areas. The task in developing action programs is to select and fit the pieces of the management puzzle together in the way that best allows the achievement of the management objective. However, before the program can evolve, or, in fact, before a realistic program objective can be developed, there must be an evaluation and ranking of the forest areas in terms of the opportunity they afford to produce specified products. This is part of the information needed for intelligent decision making.

This paper is concerned with the ranking of timber management opportunities in existing stands on National Forest land capable of producing white pine in the Forest Service's Northern Region. Presently management attention is focused on this land, partly because it is such good timber producing land and partly because the presence of blister rust in white pine has forced the Northern Region into a reevaluation of the management of white pine land. However, the evaluation techniques described here are applicable in other forest situations as well, wherever treatment alternatives exist.

INTRODUCTION

Because the Northern Region does not have an effective way to control white pine blister rust, a decision has been made to discontinue regenerating new white pine stands until rust resistant white pine planting stock is available or an economical rust control method is developed. The management problem is broader, however, than the question of what species to regenerate in place of white pine during this interim period. The white pine land[1] is largely stocked with timber, much of which is white pine. Eventually, it is hoped, the extensive research now underway will produce an effective rust control method. In the meantime the question is what to do with these stands and in what order; how to manage them in the interim period when effective control of blister rust is impossible.

This report attempts to answer the question by presenting a general method of approach to the management alternatives. The principal objective is to discuss some of the financial aspects of timber management decision making on public lands. This subject, though basic to the management of stands on white pine land, reaches beyond the problems of white pine forests.

The purpose of timber management planning on public land is, broadly speaking, threefold:

1. To produce, for a given planning period, a specified flow of timber yields consistent with both timber marketing and timber growing opportunities.

2. To select the areas best suited for producing the yields specified and to manage the selected areas in a way to achieve the most desirable balance between timber growing, recreation, watershed protection, and other forest uses.

3. To accomplish the timber growing objectives in the most economical manner possible.

A consciousness of all three aims of planning is vital to sound policy making and program development. For example, if a manager were to establish a production goal without considering rates of return possible from the forest, he might find his goal and program to be economically unrealistic. Again, if he selected for management only those stands that would individually produce the highest return on the investment, thus achieving the objective of economy, he might find it difficult if not impossible to secure the concomitant objectives of flow of yields and good coordination with other uses.

This discussion is primarily concerned with the financial ranking of stands for management treatment. Common sense dictates that all actions be considered in relation to the specified management objective, that the areas selected for timber growing be those where the objectives can be achieved at least cost, and then that the management action needed be taken in the most efficient manner possible.

Since timber management involves the expenditure of either public or private money, it is clearly desirable to choose from the available stands and management measures those that can accomplish the manager's objectives and at the same time produce the greatest dollar return on the investment. Estimations of rate of return are therefore valuable aids, and will be discussed in the following pages not as ends in themselves, but as steps in management decision making.

[1] *The term "white pine land" is used throughout this paper to designate land now growing or suitable for growing white pine. Such land is principally in Clearwater, Coeur d'Alene, Colville, Kaniksu, Kootenai, and St. Joe National Forests.*

MANAGEMENT POSSIBILITIES

Timber management possibilities in any area are limited by the capacity of the land to produce crops of wood. This capacity varies, to some extent, according to the species grown. Timber management possibilities are also limited by the nature of the stands already existing on the land. This is the primary concern of the present discussion. Land capability and species alternatives are discussed in an earlier publication in the series reporting on this study (Research Paper INT-43). They will be mentioned here only briefly.

YIELD CAPACITY OF WHITE PINE LAND

The 3.5 million acres of white pine land in the National Forests of the Northern Region includes the most productive timberland in the Rocky Mountains and is among the most productive in the United States. The white pine land of the Northern Region is now producing only a quarter to a third of the timber yields that could be realized with more intensive management. This situation exists primarily because only a portion of the forest has been converted to a regulated condition. Conversion of an old-growth forest to a condition in which the growing capacity of the land is efficiently utilized and growing stock is managed to produce a regulated flow of products is a long-term task. What can be accomplished at any one time is limited by economic circumstances and often is complicated by natural catastrophes such as fire, disease, insects, and weather. However, under management adequate to provide for prompt regeneration and stocking control the portion of this land that is site 60 or higher could produce more than 800 board feet per acre per year in an 80-year rotation. About 70 percent of land capable of growing white pine is that good.

The capacity of white pine land to produce trees is indicated in a more specific way by the data in table 1. This table shows average 10-year diameter growth rates by species for dominant and codominant trees measured on Forest Survey plots on white pine land. The growth rates shown compare favorably with growth rates in wild stands (stands that developed naturally and in which no effort has been made to control stocking) in other high timber-producing areas of the United States.

SPECIES CAPABILITIES

Even though it is not practical at this time to attempt to grow white pine on the land under study, because effective means of blister rust control are lacking, a number of other species can be grown. The most popular species that might be grown are those listed in table 1. Trees of these species now exist on the land, in some places as pure stands, but more often in stands of mixed species, often including white pine. As the growth rate data in table 1 indicate, many of the species listed grow well on white pine land.

The capacity of all the species listed to utilize the land can be influenced through management. The nature of this opportunity is partially reflected by the data in table 1. The standard deviations in growth, which are a measure of the variations in growth rates encountered, show a wide range for all species. Significantly half or more of this variation in growth can be explained by differences in stand density, tree age, and tree vigor (which is influenced by stand density), suggesting that considerable opportunity exists to improve the yield of merchantable wood through well-timed stocking control.

EXISTING STANDS

An important consideration in deciding how and when to bring a particular area or stand under management regulation is the nature of the cover already present on the

Table 1. — Average 10-year diameter growth rates by species for trees growing on white pine land

Species	Average 10-year diameter growth, all sites	Standard deviation of growth	
	Inches	*Inches*	*Percent*
White pine	2.378	1.023	43
Ponderosa pine	2.173	.821	38
Grand fir	2.131	1.003	47
Douglas-fir	1.755	.921	52
Cedar-hemlock	1.711	.864	50
Western larch	1.656	.777	47
Spruce-alpine fir	1.508	.746	49
Lodgepole pine	1.468	.782	53

Source: Forest Survey data.

land. The vegetation cover on the white pine land of the Northern Region has changed considerably in this century as a result of man's actions as well as natural factors.

Forest management started in the white pine area in the Northern Region about the turn of the century, on land supporting largely old-growth white pine timber. Since then the Forest Service has been selling timber, gradually converting the unmanaged old-growth forest to a regulated forest condition as economic limitations would permit. During this time a large volume of old-growth timber was destroyed by wildfires, disease, and insects. Today over half the forest area supports stands of sawtimber-size trees. However, sawtimber stands older than 100 years occupy only a little over a third of the area. The forest can be pictured in terms of stand size as follows:[2]

Stand size	Stand area (Thousand acres)	(Percent of total)
Sawtimber:		
Older than 160 years	586	18.2
100 to 160 years old	523	16.3
Less than 100 years old	741	23.0
Subtotal	1,850	57.5
Poletimber	620	19.2
Seedling and sapling	749	23.3
Subtotal	3,219	100.0
Nonstocked	278	
Total	3,497	

Species composition of stands varies. Although white pine is a component of many of the stands on this land today, as a result of type conversion only 12 percent of the 3.5 million acres of National Forest land capable of growing white pine actually supports stands in which white pine is the principal species. Much of this is sawtimber that can be harvested; however, as the following tabulation shows, there are 125,000 acres of white pine type containing stands of trees that are below sawtimber size:

[2] *All resource data in the tabulation were obtained from Forest Survey. All information except that presented later for young stands originating since 1949 is from surveys conducted in 1958-61. The information for the stands originating since 1949 was updated by the Northern Region from recent stand examination records and stand establishment records.*

Stand size	Thousand acres
Sawtimber	303
Poletimber	93
Seedling and sapling	32
Total	428

From even this brief description of the forest occupying white pine land, it is evident that managers hoping to improve timber production must deal with a variety of situations. Stand composition as well as stand size may vary, ranging from almost pure stands of a single species, including white pine, to stands of a variety of species mixtures. Stands may range in age from less than a year to over 200 years, and in condition from vigorous and healthy to heavily diseased and decadent. It is important to recognize also that some stands are on stable soils and gentle slopes so that they are easy to develop, whereas others are on highly unstable soils or steep slopes, or both, and may not be loggable with present technology. There is no simple answer to the management of these stands nor is there a simple solution applicable to all. *Every stand must be evaluated individually.* However, certain general considerations must be recognized with respect to white pine and other merchantable and nonmerchantable stands.

White Pine Stands

Because there is still hope for a practical method of blister rust control and research is going forward to find one, managers may wish to defer action on white pine stands if cost-value relationships would not be materially changed by a delay of a few years. This consideration would apply to mature stands as well as young stands. Again, regardless of how serious losses due to blister rust or other agents may be, it would not be wise to harvest if logging would seriously damage soil or watershed values, or both. It also may be desirable to adjust priorities in treatment planning so as to achieve yield objectives more fully.

Merchantable Stands

Some merchantable stands cannot be logged economically with present technology without undue watershed damage. However, the major consideration in dealing with merchantable stands, particularly on highly productive land, is mortality. If mortality is very light, the manager will want to defer cutting as long as possible. In stands on good land where mortality rates are high, cutting will need to be accelerated to reduce mortality losses.

Cutting for salvage in high-mortality stands appears particularly urgent in seriously threatened high-value old-growth stands of white pine. With its higher stumpage value, white pine can carry the cost of much of the access development needed to serve a multitude of land use objectives. If the white pine values are lost, large areas may have to remain without access for many years to come.

The opportunity to develop and log an area economically can be quickly lost as mortality increases. The Northern Region has about 150,000 acres of mature white pine timber type in areas largely inaccessible. Much of this timber is in stands yet to be inventoried in sufficient detail to indicate mortality, but in those stands that have been surveyed, 5 to 7 percent of white pine timber has been dying each year.

Data from the Forest Survey indicate the nature of the problem of mortality. The volume of salvable dead timber[3] reflects the more recent mortality: 38,000 acres support sawtimber stands containing 1,500 cubic feet (roughly 7,500 board feet) or more in salvable dead trees per acre, as the following tabulation shows:

Volume of salvable dead wood (Cu. ft./acre)	Approximate board feet per acre	Thousand acres
Less than 499	1,250	1,699
500-999	3,750	81
1,000-1,499	6,750	33
1,500-1,999	8,750	18
2,000-2,499	11,250	9
2,500-2,999	13,750	7
Over 3,000	15,000+	4
Total		1,851

[3] *Dead merchantable trees containing 50 percent or more sound wood at the time of measurement.*

The harvesting opportunity is limited as well by the volume of timber available per acre and by the cost of road development. In developed areas it is sometimes possible to harvest volumes of 1,000 board feet per acre or less. Data are lacking to show timber available in relation to development cost. Generally speaking, timber can be harvested if the volume available in trees of merchantable size over large areas exceeds 5,000 board feet per acre, unless problems of access and development are severe. Of the 1,850,000 acres of sawtimber in the study area, 1,633,000 acres support 5,000 board feet or more per acre.

One of the more urgent problems facing the Northern Region is to complete an inventory of white pine stands of harvestable size and determine priorities for harvesting.

Nonmerchantable Stands

The nonmerchantable stands, like the merchantable stands, represent a wide range of situations, and each stand has to be considered individually. Also, each stand has to be considered in relation to the operability and quality of the land it is growing on and in relation to the management goals set for the Forest.

Depending on their age, size, vigor, and species composition, and on the quality and character of the land on which they are growing, nonmerchantable stands present a variety of possibilities. Some may offer few management opportunities either because nature alone is doing a good job or because any improvements in the yield would be small in relation to the costs involved. In addition, some of the pure or almost pure white pine stands are so near gone that there is no alternative but to start over with a new stand of some other species or mixture of other species.

The majority of the immature stands, however, are mixed species. If these are overstocked, thinning is always a management possibility. Any diseased white pine trees in these stands can be removed in the thinning treatment.

Stands in the younger age classes (fig. 1) are generally thought to offer the best thinning opportunities, because capabilities for growth response generally decrease with age as well as with increases in stocking and loss of crown. According to surveys made in 1958-61, of the 1,368,000 acres of pole size and smaller timber, 693,000 acres supported stands that originated after 1929, and of these, 121,000 acres supported stands that originated after 1949. Since the 1958-61 survey, an additional 100,000 acres of new stands have been established on white pine land, 52,000 acres by planting and 48,000 by natural regeneration.

For the most part these stands are well stocked with potential crop trees[4] that will produce good timber products. Many of the 221,000 acres of stands originating since 1949 have already been examined to evaluate thinning opportunities, and data from these examinations suggest that most of this land is well stocked in terms of potential crop trees. These data suggest that if the stands examined are representative of the 221,000 acres, then 190,000 acres have 200 or more potential crop trees per acre, in the following proportions:

Potential crop trees per acre	Thousand acres
Less than 100	2
100 – 199	29
200 – 299	60
300 – 400	86
Over 500	44
Total	221

One of the problems of this area is that the potential crop trees are growing in competition with many trees that are excess to the needs of the stands. Some stands, principally plantations, have relatively few excess trees per acre. However, one-third of the stands that

[4] *In stand examinations, potential crop trees are identified with reference to tree quality and distribution. These are the trees that would be featured if the stand were to be thinned.*

Figure 1. – Thinning in a young stand of lodgepole pine in the Northern Region.

originated since 1949 have 1,000 or more excess trees per acre, as follows:

Excess trees per acre	Thousand acres
Less than 199	71
200 – 499	44
500 – 999	32
1,000 – 1,999	46
2,000 – 2,999	13
3,000 or more	15
Total	221

Managers may also wish to consider methods of improving wood quality yield by pruning. Pruning might help to control dwarfmistletoe, which infects some nonmerchantable stands.[5] However, the practicability of this method has yet to be demonstrated in this Region. Dwarfmistletoe might also be controlled through eradication of infected and exposed trees during the thinning process.

[5] *Flora, Donald F. A method of forecasting returns from ponderosa pine dwarfmistletoe control. U.S. Forest Serv. Res. Pap. PNW-37, 17 pp. 1966.*

Some nonmerchantable stands are residual stands of cull timber. Included in the forest on white pine land are 83,000 acres supporting stands containing 3,000 cubic feet or more per acre of cull sawtimber. Some of this land is excellent for timber production site class 80 or better; about half is site index 60 or better:

Site class	Thousand acres
80+	10
70	12
60	17
50	23
40	21
Total	83

The site class for most of this land is based on measurement of old residual cull trees, which usually results in an underestimate of site. In many instances these cull stands can be removed inexpensively under salvage contracts, making the land available to grow a new crop. In others, it may be possible to fell and burn residual stands so that the land can be used.

Table 3. — Total volume of all trees 0.6 inch d.b.h. and larger for normal white pine stands

Age	Site index			
	50	60	70	80
	Cubic feet per acre			
40	2,270	2,650	3,030	3,400
50	3,640	4,210	4,830	5,470
60	5,050	5,880	6,710	7,600
70	6,450	7,500	8,560	9,730
80	7,750	9,000	10,350	11,750
90	8,980	10,450	12,000	13,650
100	10,100	11,850	13,500	15,400
110	11,150	13,000	14,800	16,850

Source: Haig, Irvine T. Second growth yield, stand and volume tables for the western white pine type. U.S. Dep. Agr. Tech. Bull. 323, 68 pp. 1932.

ning, fully stocked western larch stands on site 70 land should produce 4,682 cubic feet of wood at age 50 in trees 8 inches and larger and that 8-inch trees can be utilized. In other words, it is expected that an additional 2,500 cubic feet of wood per acre will be available in trees 8 inches and larger at age 50 as a result of thinning. The above information is shown graphically in figure 3.

It is well to recognize the low state of the art of projecting stands under different levels of management. However, in ranking stands for management treatment, the crudity of stand projection techniques need not be a serious handicap so long as there is no evidence of bias. It is essential only that the procedures and data used produce results that are consistent from stand to stand.

Estimating future wood prices is even more difficult than predicting stand response to treatment. No one can say definitely what wood will be worth 50 or 100 years in the future or how prices will vary between species. After studying price trends, the manager must judge what future prices are likely to be, but he must recognize that his conclusion is largely guesswork.

A recent analysis of wood selling prices (Research Note INT-65 in this series) indicates that the high prices of white pine and ponderosa pine are largely the result of the demand for the clear wood of these species. Unless stands are pruned or rotations are lengthened, the price differences between white and ponderosa pine and other species may be less in the future. It is probable that species price differences will be negligible in stands just achieving merchantable size. However, it is also probable that wood value increases with tree size in some species more than in others.

Even though species price differences have been lessening in recent years, the manager may still wish to recognize some differences in establishing prices to be used in evaluating timber growing opportunities.

Accessibility to market may be a desirable point to consider, and a range of prices by species that reflects distance from principal processing centers might be established. However, if analyses of individual stands are to be comparable, the price estimates applied to similar stands that are to be managed in the same way must be the same.

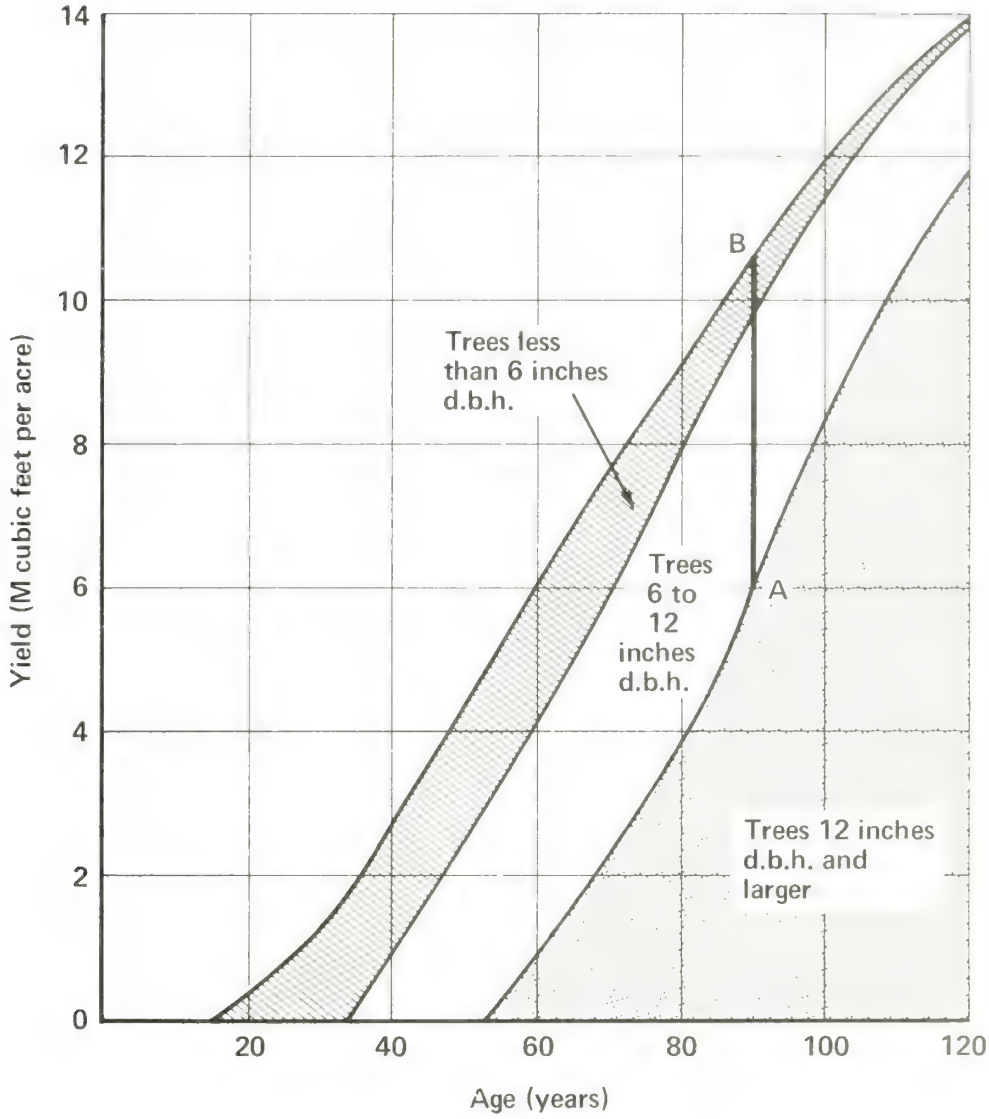

Figure 2. Volume by tree size class in fully stocked wild stands of white pine, site class 60.

TIME PERIOD ESTIMATES MUST BE CONSISTENT

Two aspects of time are important in financial calculations. First, there are the specific times when incomes are expected or expenditures are to be made. Second, there is the overall time period, the rotation planned for a timber growing operation.

Depending on the circumstances surrounding the management of a Forest, the effects of a particular management treatment may be immediate or may be realized at some later point in time. To illustrate, if the annual allowable cut were to increase immediately because of some management action, the financial calculations would be based on the net value of the increase in cut for as long as it persisted. On the other hand, if the benefits were not realized until some future date during or at the end of the rotation, the calculation of rate of return would have to take account of the elapsed time.

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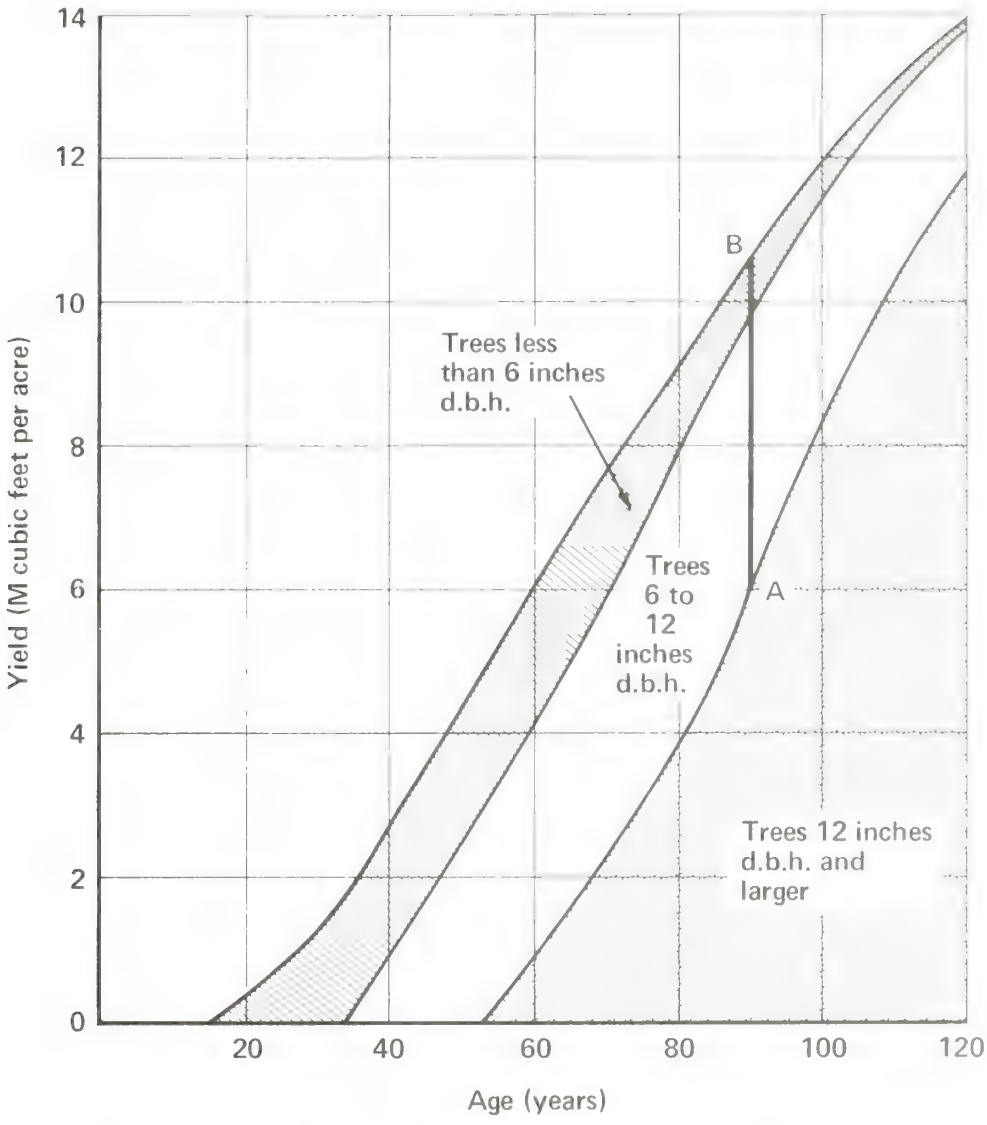


Figure 2. Volume by tree size class in fully stocked wild stands of white pine, site class 60.

TIME PERIOD ESTIMATES MUST BE CONSISTENT

Two aspects of time are important in financial calculations. First, there are the specific times when incomes are expected or expenditures are to be made. Second, there is the overall time period, the rotation planned for a timber growing operation.

Depending on the circumstances surrounding the management of a Forest, the effects of a particular management treatment may be immediate or may be realized at some later point in time. To illustrate, if the annual allowable cut were to increase immediately because of some management action, the financial calculations would be based on the net value of the increase in cut for as long as it persisted. On the other hand, if the benefits were not realized until some future date during or at the end of the rotation, the calculation of rate of return would have to take account of the elapsed time.

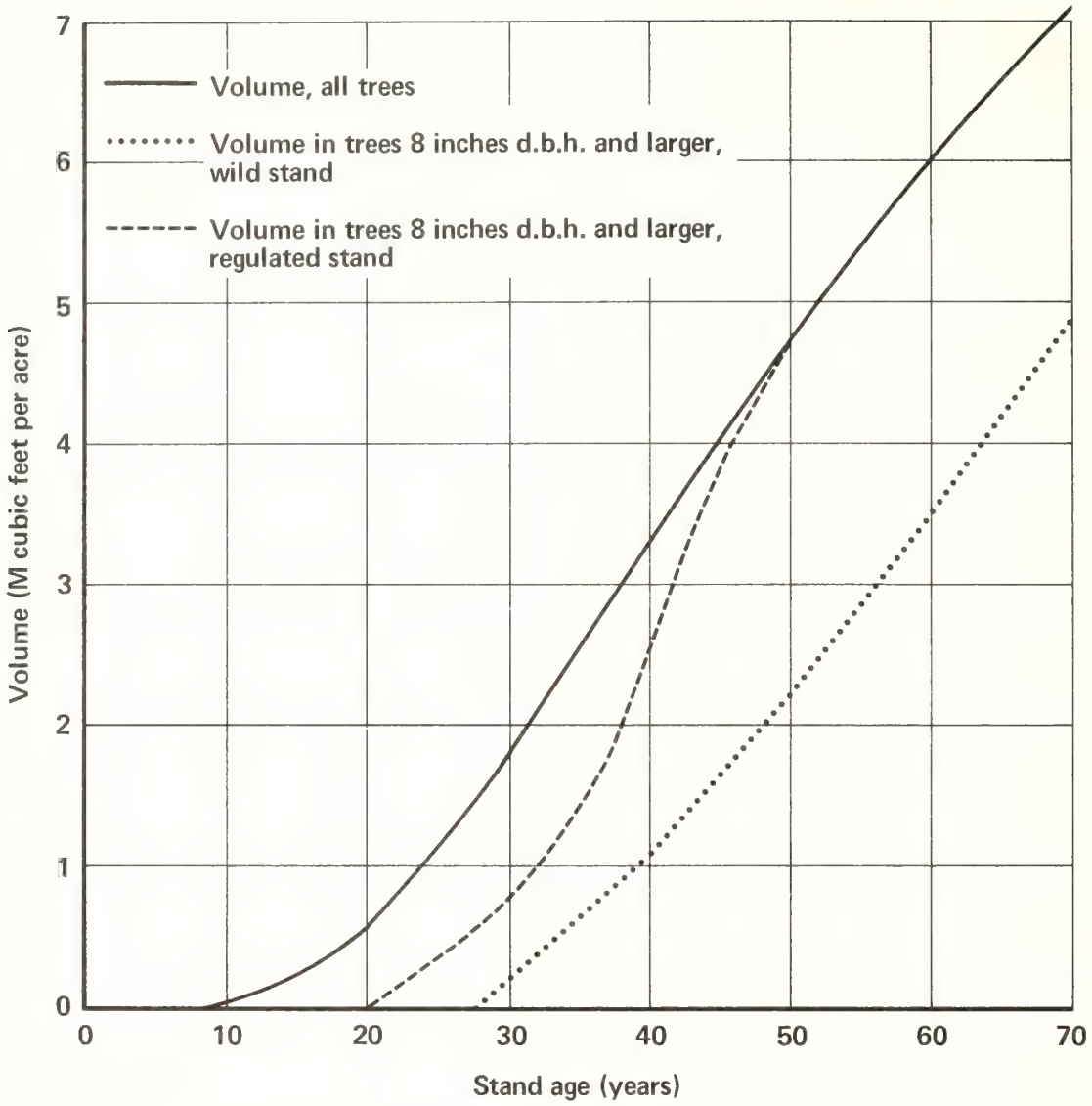


Figure 3. — Expected development of fully stocked western larch stand with and without stocking control, as represented by volume in different tree size classes.

In both situations, however, the aim is to compare the estimated cost of the management treatment being considered with the expected effect on yield, considering the time that will elapse between the point when the cost is incurred and the point when benefit is realized.

The time period or rotation used is an important element in financial calculations. However, it must be recognized here that there is a certain element of guesswork in the establishment of timber rotations. Circumstances are continually changing in a way that may affect the length of the timber growing period. Harvesting may be required short of the rotations established, to avoid serious loss due to some forest enemy. Similarly, technology or wood values may change, making either a shortening or lengthening of rotations desirable.

The Northern Region has established some tentative rotations and tree-size objectives by

site classes. These are not economic rotations in that they are not supported by economic analysis. They may be longer or shorter than is desirable from a timber growing cost-price point of view. As illustrated in table 4, on the basis of yield data for white pine (site index 70), only under the first of the two price assumptions (which were arbitrarily chosen) is the rate of value increase greater than 5 percent after age 90. The rate of value increase reflected in either set of price assumptions may or may not be reasonable.

Northern Region tentative tree-size objectives and rotations are as follows:

Site class based on height at 50 years	Average diameter (Inches)	Rotation (Years)
White pine, grand fir, spruce, hemlock		
90+	22	90
70 – 80	20	100
50 – 60	18	110
40 – 50	16	120
Larch, Douglas-fir, ponderosa pine		
90+	20	100
70 – 80	18	110
50 – 60	16	120
40 and less	Cordwood	
Lodgepole pine		
60+	16	80
40 – 50	14	100
Less than 40	Cordwood	

In the actual practice of timber growing, the rotation period tends to be indefinite. Quite probably in the future, the termination of stand growing periods will be decided as each stand takes on merchantable value. Some stands may be held for long periods to produce products to meet particular demands. Other stands may be cut as soon as they become merchantable.

Although it is desirable to have available an established scale of economically defensible timber growing periods for broad planning purposes, that question need not be dealt with here since this discussion is concerned only with the ranking of opportunities within a particular locality. In ranking stands or areas for management treatment within a Region or within a Forest, the time periods used need not represent a serious source of bias as long as they are reasonably consistent for the entire area. It is important to recognize that in evaluating long-term production opportunities such as timber growing, consistency in procedure and data is very important.

Table 4. – Rate of stand value increase under two price assumptions – yield data for white pine site index 70

Age	Volume per acre	Assumption 1			Assumption 2		
		Price per M bd. ft.	Stand value per acre	Rate of value increase	Price per M bd. ft.	Stand value per acre	Rate of value increase
	M bd.ft.	*- Dollars – – – – –*		*Percent*	*– – – Dollars – – –*		*Percent*
50	19.5	4.00	78.00	—	4.00	78.00	—
60	33.8	6.00	202.80	10.0	6.00	202.80	10.0
70	44.8	9.00	403.20	7.5	8.00	358.40	5.9
80	63.5	13.00	825.50	6.5	10.00	635.00	5.7
90	78.0	18.00	1,404.00	5.5	12.00	936.00	4.0
100	90.5	24.00	2,172.00	4.5	14.00	1,267.00	3.1
110	100.9	32.00	3,228.80	4.0	16.00	1,614.40	2.5

Source: Haig, Irvine T. Second growth yield, stand and volume tables for the western white pine type. U.S. Dep. Agr. Tech. Bull. 323, 68 pp. 1932.

The calculation of rate of return is quite complicated when a series of costs as well as a series of returns are involved. Computer programs have been prepared by both Hall and Row[6] for making present worth and interest rate computations. These programs have been adapted by the Intermountain Station for use on the Forest Service's Northern and Intermountain Regions' computers to handle common evaluation problems of timber growing. Basic adaptations of both Hall's and Row's programs are described by Green and Alley for use in ranking species alternatives (Research Paper INT-42 in this series). The discussion here describes another version of the Clark Row program usable in ranking opportunities in existing stands and in evaluating timber stand improvement programs. Use of the program is illustrated in brief in the pages that follow. Details of the program are presented in the Appendix.

[6] *Hall, Otis. Evaluating complex investments in forestry and other long-term enterprises using a digital computer. Purdue Univ. Res. Bull. 752, 11 pp. 1962. Row, Clark. Determining forest investment rates of return by electronic computer, U.S. Forest Serv. Res. Pap. SO-6, 13 pp. 1963.*

RANKING STANDS FOR REPLACEMENT

The program given here is identified as Intermountain Station Investment Analysis Program No. 6. (The program listing is given in the Appendix.) Among other things, this program will compute discounted net worth[7] of future crops and discounted net worth of the present and future crops combined.

There are two common uses for this feature of the program. First of all, the program can be used to determine, from a financial standpoint, which stands should be considered for immediate cutting. To illustrate, if present net worth for a stand would be increased significantly if the stand were held for another 10-year planning period, considering both the value changes in the present stand and the future growing opportunity, the manager would not want to program it for cutting now. From an economic point of view a manager might want to hold the stand described below:

[7] *Discounted net worth is the computed present net value of the area, assuming a specified rate of return.*

	Alternative 1 (cut now)	Alternative 2 (cut in 10 years)
Present stand and conversion opportunity		
Estimated merchantable volume (100 cubic feet per acre)	70	80
Quality index	.90	1.10
Future timber growing opportunity		
Site preparation year after cutting (cost, dollars per acre)	5.00	5.00
Regeneration (cost, dollars per acre)	.00	.00
Precommercial thinning 21 years after site preparation (cost, dollars per acre)	22.00	22.00
Intermediate cut 30 years after thinning (100 cubic feet per acre)	25	25

	Alternative 1 (cut now)	Alternative 2 (cut in 10 years)
Quality index for intermediate cut	.35	.35
Harvest cut 30 years after intermediate cut (100 cubic feet per acre)	90	90
Quality index for harvest cut	1.10	1.10
Price assumption		
Net price (dollars per 100 cubic feet)	5.00	5.00
Expected increase in price per year (rate)	.005	.005

Note that for both the present and the future stands the anticipated schedule of investments and yields is listed. In each case quality of yield is indicated.[8] Note also that it has been assumed that real wood prices will increase slightly in the future (0.5 percent per year). The program provides the opportunity to assign current prices to products and include an estimate of how prices are expected to change over time.

For use with the computer program, the data in the above tabulation must be prepared for computer input. (Instructions for preparing problem input are given in the Appendix.)

The problem solution is shown in figure 4. After printing the program input, the computer lists the discounted net worth of future crops. This listing also reveals the expected internal rate of return in future timber growing if the range of interest rates specified includes the rate at which present worth is $0.00.

In this case expected internal rate of return on future timber growing is between 5.6 and 5.7 percent. It is between these rates that discounted net worth becomes zero. This listing is included in the output to help the manager decide whether to consider timber growing on the area if investments are required.

The second listing shows discounted net worth for the present and future stands. This listing shows that present worth for alternative 2 is still greater than for alternative 1 at 3.5 percent rate of return. This may be considered a lower rate of return than is desirable, but because managers in this area have so much timber in need of cutting, they may want to hold this stand and fill cutting budgets from stands for which present worth was decreasing with time, assuming the same rate of return.

In addition to using the investment analysis computer program to check his judgments about what stands to consider for cutting, the manager can also use the program to establish cutting priorities among stands ready for cutting. If a manager were not forced to cut in a specific area to control the spread of some forest infection, he logically would cut in those areas where (again considering present stand value and the future timber growing opportunity) the greatest contribution to revenue could be made. Here, again, costs and values associated with both the present stand and the future stand would be considered.

The present stand and the future timber growing opportunity on two areas described in the following tabulation are used for illustration.

	Area 1	Area 2
Present stand and conversion opportunity		
Merchantable volume per acre (100 cubic feet per acre)	74	50

[8] *The quality index is the ratio of the estimated price for the specific product to the average price expected for the product.*

	Area 1	Area 2
Quality index	.90	.90
Road costs 1 year before logging (dollars per acre)	24.00	22.00
Sales cost 2 years before logging (dollars per acre)	7.00	6.00
Future timber growing opportunity		
Thinning 30 years after logging on poor land, 15 years after logging on good land (dollars per acre)	23.00	23.00
Intermediate yield 45 years after thinning on poor land, 35 years after thinning on good land (100 cubic feet per acre)	—	20.00
Quality index	—	.35
Intermediate cut 50 years after thinning (100 cubic feet per acre)	25.00	30.00
Quality index	.35	.50
Harvest yield 80 years after thinning on poor land, 66 years after thinning on good land (100 cubic feet per acre)	80.00	120.00
Quality index	.90	1.40
Price assumption		
Price (dollars per 100 cubic feet)	7.00	7.00
Expected increase in price per year (rate)	.005	.005

The problem solution is shown in figure 5. The computer lists discounted present worth of future crops for the range of interest rates specified. This listing also reveals the expected internal rate of return in future timber growing. In the case of area 1 it is between 4.8 and 4.9 percent. Between these rates, discounted net worth becomes zero. For area 2 the expected internal rate of return is much higher – between 7.4 and 7.5 percent.

The second listing shows the discounted net worth of the present and future stands. If, in ranking stands, 3.6 percent were set as the point at which stands would be cut, a manager would cut area 2 in preference to area 1 because, as this listing shows, discounted net worth is greater by $2.64. To the extent that a manager could fill his cutting budget from areas like area 2, he would defer cutting areas like area 1.

RANKING STAND IMPROVEMENT PROJECTS

Investment Analysis Program No. 6 can also be used for evaluating timber stand improvement opportunities when the manager is concerned about cost in relation to the margin of difference resulting from treatment. For example, assume a manager has a heavily overstocked 20-year old stand: if he did nothing the stand would yield a harvest cut of 6,000 cubic feet of merchantable wood (about 30,000 board feet) in 100 years (at age 120). He might wish to know what the advantage would be of precommercial thinning and pruning. With precommercial thinning he might expect two commercial thinnings, one of 1,200 cubic feet (about 5,000 board feet) in 35 years (at age 55), and one of 2,000 cubic

Figure 4. — Problem solution (see problem 4, Appendix).

PROBLEM NO. 4--SAMPLE PROBLEM--STAND REPLACEMENT--CUT NOW OR IN 10 YEARS

DISCOUNTED NET WORTH OF FUTURE CROPS

RATE	ALT-PLAN 1 (ROTATION 81)	ALT-PLAN 2 (ROTATION 81)	ALT-PLAN 0 (ROTATION 0)
1.0	579.90	579.90	
1.1	503.11	503.11	
1.2	439.82	439.82	
1.3	386.91	386.91	
1.4	342.14	342.14	
1.5	303.88	303.88	
1.6	270.90	270.90	
1.7	242.26	242.26	
1.8	217.23	217.23	
1.9	195.22	195.22	
2.0	175.78	175.78	
2.1	158.53	158.53	
2.2	143.17	143.17	
2.3	129.45	129.45	
2.4	117.14	117.14	
2.5	106.08	106.08	
2.6	96.11	96.11	
2.7	87.10	87.10	
2.8	78.95	78.95	
2.9	71.56	71.56	
3.0	64.85	64.85	
3.1	58.75	58.75	
3.2	53.19	53.19	
3.3	48.12	48.12	
3.4	43.50	43.50	
3.5	39.27	39.27	
3.6	35.41	35.41	
3.7	31.87	31.87	
3.8	28.63	28.63	
3.9	25.66	25.66	
4.0	22.94	22.94	
4.1	20.44	20.44	
4.2	18.14	18.14	
4.3	16.04	16.04	
4.4	14.10	14.10	
4.5	12.32	12.32	
4.6	10.69	10.69	
4.7	9.19	9.19	
4.8	7.81	7.81	
4.9	6.54	6.54	
5.0	5.37	5.37	
5.1	4.30	4.30	
5.2	3.31	3.31	
5.3	2.40	2.40	
5.4	1.57	1.57	
5.5	.80	.80	
5.6	.09	.09	
5.7	-0.55	-0.55	
5.8	-1.15	-1.15	
5.9	-1.69	-1.69	
6.0	-2.19	-2.19	
6.1	-2.65	-2.65	
6.2	-3.07	-3.07	
6.3	-3.46	-3.46	
6.4	-3.81	-3.81	
6.5	-4.13	-4.13	
6.6	-4.43	-4.43	
6.7	-4.70	-4.70	
6.8	-4.94	-4.94	
6.9	-5.17	-5.17	
7.0	-5.37	-5.37	

PROBLEM NO. 4--SAMPLE PROBLEM--STAND REPLACEMENT--CUT NOW OR IN 10 YEARS

DISCOUNTED NET WORTH OF PRESENT AND FUTURE CROPS

RATE	ALT-PLAN 1 (ROTATION 0)	ALT-PLAN 2 (ROTATION 10)	ALT-PLAN 0 (ROTATION 0)
1.0	894.90	943.22	
1.1	818.11	865.10	
1.2	754.82	800.41	
1.3	701.91	746.05	
1.4	657.14	699.77	
1.5	618.88	659.94	
1.6	585.90	625.33	
1.7	557.26	595.01	
1.8	532.23	568.25	
1.9	510.22	544.46	
2.0	490.78	523.20	
2.1	473.53	504.09	
2.2	458.17	486.82	
2.3	444.45	471.15	
2.4	432.14	456.86	
2.5	421.08	443.78	
2.6	411.11	431.76	
2.7	402.10	420.68	
2.8	393.95	410.42	
2.9	386.56	400.90	
3.0	379.85	392.03	
3.1	373.75	383.74	
3.2	368.19	375.99	
3.3	363.12	368.70	
3.4	358.50	361.84	
3.5	354.27	355.36	
3.6	350.41	349.23	
3.7	346.87	343.42	
3.8	343.63	337.89	
3.9	340.66	332.63	
4.0	337.94	327.61	
4.1	335.44	322.80	
4.2	333.14	318.20	
4.3	331.04	313.78	
4.4	329.10	309.52	
4.5	327.32	305.43	
4.6	325.69	301.48	
4.7	324.19	297.66	
4.8	322.81	293.97	
4.9	321.54	290.39	
5.0	320.37	286.92	
5.1	319.30	283.55	
5.2	318.31	280.27	
5.3	317.40	277.08	
5.4	316.57	273.97	
5.5	315.80	270.94	
5.6	315.09	267.97	
5.7	314.45	265.08	
5.8	313.85	262.24	
5.9	313.31	259.47	
6.0	312.81	256.75	
6.1	312.35	254.09	
6.2	311.93	251.48	
6.3	311.54	248.91	
6.4	311.19	246.39	
6.5	310.87	243.92	
6.6	310.57	241.48	
6.7	310.30	239.09	
6.8	310.06	236.73	
6.9	309.83	234.41	
7.0	309.63	232.13	

Figure 5. — Problem solution (see problem 5, Appendix).

PROBLEM NO. 5--SAMPLE PROBLEM--STAND REPLACEMENT -COMPARISON OF 2 STANDS

DISCOUNTED NET WORTH OF FUTURE CROPS

RATE	ALT-PLAN 3 (ROTATION 110)	ALT-PLAN 7 (ROTATION 81)	ALT-PLAN 0 (ROTATION 0)
1.0	413.13	1438.99	
1.1	351.73	1252.02	
1.2	301.59	1097.88	
1.3	260.11	968.96	
1.4	225.39	859.84	
1.5	196.06	766.54	
1.6	171.09	686.07	
1.7	149.70	616.15	
1.8	131.26	555.00	
1.9	115.29	501.21	
2.0	101.40	453.67	
2.1	89.27	411.45	
2.2	78.65	373.82	
2.3	69.33	340.16	
2.4	61.12	309.96	
2.5	53.88	282.78	
2.6	47.48	258.26	
2.7	41.81	236.09	
2.8	36.79	216.00	
2.9	32.34	197.76	
3.0	28.39	181.18	
3.1	24.87	166.07	
3.2	21.74	152.29	
3.3	18.96	139.71	
3.4	16.48	128.20	
3.5	14.28	117.67	
3.6	12.31	108.02	
3.7	10.56	99.17	
3.8	9.01	91.04	
3.9	7.62	83.58	
4.0	6.38	76.71	
4.1	5.28	70.40	
4.2	4.31	64.59	
4.3	3.44	59.24	
4.4	2.67	54.30	
4.5	1.99	49.76	
4.6	1.38	45.56	
4.7	.85	41.69	
4.8	.38	38.12	
4.9	-0.04	34.83	
5.0	-0.40	31.78	
5.1	-0.72	28.97	
5.2	-1.00	26.37	
5.3	-1.25	23.97	
5.4	-1.46	21.75	
5.5	-1.64	19.69	
5.6	-1.80	17.80	
5.7	-1.93	16.04	
5.8	-2.05	14.42	
5.9	-2.14	12.92	
6.0	-2.22	11.53	

PROBLEM NO. 5--SAMPLE PROBLEM--STAND REPLACEMENT -COMPARISON OF 2 STANDS

DISCOUNTED NET WORTH OF PRESENT AND FUTURE CROPS

RATE	ALT-PLAN 3 (ROTATION 3)	ALT-PLAN 7 (ROTATION 3)	ALT-PLAN 0 (ROTATION 0)
1.0	829.80	1735.34	
1.1	767.88	1549.23	
1.2	717.20	1395.89	
1.3	675.13	1267.71	
1.4	639.80	1159.26	
1.5	609.82	1066.59	
1.6	584.19	986.68	
1.7	562.09	917.27	
1.8	542.92	856.57	
1.9	526.19	803.18	
2.0	511.52	755.99	
2.1	498.59	714.07	
2.2	487.14	676.70	
2.3	476.97	643.24	
2.4	467.89	613.20	
2.5	459.76	586.13	
2.6	452.46	561.69	
2.7	445.88	539.55	
2.8	439.92	519.45	
2.9	434.52	501.17	
3.0	429.60	484.50	
3.1	425.11	469.28	
3.2	420.99	455.35	
3.3	417.21	442.58	
3.4	413.73	430.86	
3.5	410.50	420.08	
3.6	407.51	410.15	
3.7	404.73	401.00	
3.8	402.14	392.54	
3.9	399.71	384.73	
4.0	397.42	377.48	
4.1	395.27	370.77	
4.2	393.24	364.54	
4.3	391.31	358.74	
4.4	389.47	353.35	
4.5	387.72	348.32	
4.6	386.05	343.63	
4.7	384.45	339.24	
4.8	382.90	335.14	
4.9	381.42	331.30	
5.0	379.98	327.69	
5.1	378.58	324.30	
5.2	377.23	321.12	
5.3	375.92	318.12	
5.4	374.63	315.28	
5.5	373.38	312.61	
5.6	372.15	310.08	
5.7	370.95	307.69	
5.8	369.77	305.42	
5.9	368.62	303.26	
6.0	367.48	301.21	

6.1	-2.28	10.25
6.2	-2.33	9.06
6.3	-2.37	7.96
6.4	-2.40	6.95
6.5	-2.42	6.01
6.6	-2.43	5.14
6.7	-2.43	4.34
6.8	-2.43	3.60
6.9	-2.42	2.92
7.0	-2.41	2.29
7.1	-2.39	1.71
7.2	-2.37	1.17
7.3	-2.34	.68
7.4	-2.32	.22
7.5	-2.29	-0.20
7.6	-2.25	-0.59
7.7	-2.22	-0.94
7.8	-2.18	-1.27
7.9	-2.15	-1.57
8.0	-2.11	-1.84
8.1	-2.07	-2.10
8.2	-2.03	-2.33
8.3	-1.99	-2.54
8.4	-1.96	-2.73
8.5	-1.92	-2.91
8.6	-1.88	-3.07
8.7	-1.84	-3.21
8.8	-1.80	-3.34
8.9	-1.76	-3.46
9.0	-1.72	-3.57
9.1	-1.68	-3.66
9.2	-1.64	-3.75
9.3	-1.61	-3.82
9.4	-1.57	-3.89
9.5	-1.53	-3.95
9.6	-1.50	-4.00
9.7	-1.46	-4.04
9.8	-1.43	-4.08
9.9	-1.39	-4.11
10.0	-1.36	-4.14

6.1	366.35	299.25
6.2	365.24	297.39
6.3	364.15	295.61
6.4	363.07	293.91
6.5	362.00	292.27
6.6	360.94	290.71
6.7	359.89	289.20
6.8	358.85	287.76
6.9	357.82	286.36
7.0	356.80	285.02
7.1	355.78	283.72
7.2	354.77	282.46
7.3	353.77	281.24
7.4	352.77	280.06
7.5	351.78	278.91
7.6	350.80	277.80
7.7	349.82	276.71
7.8	348.84	275.65
7.9	347.87	274.62
8.0	346.90	273.61
8.1	345.94	272.63
8.2	344.98	271.66
8.3	344.03	270.72
8.4	343.08	269.79
8.5	342.13	268.88
8.6	341.18	267.98
8.7	340.24	267.11
8.8	339.31	266.24
8.9	338.37	265.39
9.0	337.44	264.55
9.1	336.51	263.72
9.2	335.59	262.91
9.3	334.67	262.10
9.4	333.75	261.31
9.5	332.83	260.52
9.6	331.92	259.74
9.7	331.01	258.97
9.8	330.10	258.21
9.9	329.20	257.46
10.0	328.30	256.71

feet (about 10,000 board feet) in 55 years (at age 75), and a harvest cut of 11,000 cubic feet (70,000 board feet) in 80 years (at age 100). It is estimated that with pruning the value of the harvest cut would be increased 65 percent. The costs and yields are summarized as follows:

Costs	No management			With management (Dollars)		
Thinning				26.00		
Pruning				30.00		
Yields	**Age**	**Volume (M bd.ft.)**	**Quality index**	**Year**	**Volume (M bd.ft.)**	**Quality index**
1st thinning	—	—	—	35	5	0.20
2nd thinning						
Without pruning	—	—	—	55	10	.80
With pruning	—	—	—	55	10	.85
Harvest						
Without pruning	100	30.0	.90	80	70	1.10
With pruning	—	—	—	80	70	1.75

Basic stumpage price = $10 per thousand board feet changing at the rate of 0.5 percent per year.

The questions the manager would want answered are (1) What will the additional merchantable yield resulting from thinning mean in terms of rate of return – in other words, what would be the rate of return on the added expenditure required to do the thinning? and (2) Would the value that could be added by pruning be sufficient to justify the expenditure?

The manager could work the problem out by hand, or he could describe his plans in such a way that they could be submitted for solution by computer. For example, in one comparison a timber growing program requiring thinning only can be compared with a timber growing program requiring no cultural work. A second comparison can be made between a timber growing program that includes both thinning and pruning with one requiring no cultural work.

Figure 6 shows the output and illustrates the nature of the machine calculation. Present discounted net worth for each timber growing program, in the comparisons for the range of interest rates specified, is shown first. The program then computes the present discounted net worth of the difference due to the added treatment for the range of interest rates specified. The interest rate shown at the point where present worth of the difference changes from a positive to a negative value is the rate earned. In the case of thinning compared with a plan of management that did not include thinning, the rate of return on the input for thinning is between 5.2 and 5.3 percent. The input for thinning and pruning in the second comparison would earn between 4.5 and 4.6 percent indicating that pruning only lessened the financial value of the timber growing opportunity.

Figure 6. Problem solution (see problem 6, Appendix).

PROBLEM NO. 6--SAMPLE PROBLEM--TSI OPTION WITH 2 COMPARISONS

DISCOUNTED NET WORTH--FIRST TSI PLAN

RATE	ALT_PLAN 1 (ROTATION 100)	ALT_PLAN 2 (ROTATION 100)	ALT_PLAN 0 (ROTATION 0)
1.0	149.73	149.73	
1.1	135.62	135.62	
1.2	122.86	122.86	
1.3	111.30	111.30	
1.4	100.85	100.85	
1.5	91.38	91.38	
1.6	82.81	82.81	
1.7	75.05	75.05	
1.8	68.03	68.03	
1.9	61.66	61.66	
2.0	55.90	55.90	
2.1	50.69	50.69	
2.2	45.96	45.96	
2.3	41.68	41.68	
2.4	37.80	37.80	
2.5	34.28	34.28	
2.6	31.10	31.10	
2.7	28.21	28.21	
2.8	25.59	25.59	
2.9	23.22	23.22	
3.0	21.07	21.07	
3.1	19.12	19.12	
3.2	17.36	17.36	
3.3	15.76	15.76	
3.4	14.30	14.30	
3.5	12.98	12.98	
3.6	11.79	11.79	
3.7	10.70	10.70	
3.8	9.72	9.72	
3.9	8.83	8.83	
4.0	8.02	8.02	
4.1	7.28	7.28	
4.2	6.62	6.62	
4.3	6.01	6.01	
4.4	5.46	5.46	
4.5	4.96	4.96	
4.6	4.51	4.51	
4.7	4.10	4.10	
4.8	3.73	3.73	
4.9	3.39	3.39	
5.0	3.08	3.08	
5.1	2.80	2.80	
5.2	2.55	2.55	
5.3	2.32	2.32	
5.4	2.11	2.11	
5.5	1.92	1.92	
5.6	1.74	1.74	
5.7	1.58	1.58	
5.8	1.44	1.44	
5.9	1.31	1.31	
6.0	1.19	1.19	
6.1	1.09	1.09	
6.2	.99	.99	
6.3	.90	.90	

PROBLEM NO. 6--SAMPLE PROBLEM--TSI OPTION WITH 2 COMPARISONS

DISCOUNTED NET WORTH--FIRST TSI PLAN

RATE	ALT_PLAN 1 (ROTATION 100)	ALT_PLAN 2 (ROTATION 100)	ALT_PLAN 0 (ROTATION 0)
6.4	.82	.82	
6.5	.75	.75	
6.6	.68	.68	
6.7	.62	.62	
6.8	.56	.56	
6.9	.51	.51	
7.0	.47	.47	
7.1	.43	.43	
7.2	.39	.39	
7.3	.35	.35	
7.4	.32	.32	
7.5	.29	.29	
7.6	.27	.27	
7.7	.24	.24	
7.8	.22	.22	
7.9	.20	.20	
8.0	.18	.18	
8.1	.17	.17	
8.2	.15	.15	
8.3	.14	.14	
8.4	.13	.13	
8.5	.12	.12	
8.6	.11	.11	
8.7	.10	.10	
8.8	.09	.09	
8.9	.08	.08	
9.0	.07	.07	
9.1	.07	.07	
9.2	.06	.06	
9.3	.06	.06	
9.4	.05	.05	
9.5	.05	.05	
9.6	.04	.04	
9.7	.04	.04	
9.8	.04	.04	
9.9	.03	.03	
10.0	.03	.03	

PROBLEM NO. 6--SAMPLE PROBLEM--TSI OPTION WITH 2 COMPARISONS

DISCOUNTED NET WORTH--SECOND TSI PLAN

RATE	ALT-PLAN 1 (ROTATION 80)	ALT-PLAN 2 (ROTATION 80)	ALT-PLAN 0 (ROTATION 0)
1.0	540.05	794.88	
1.1	499.20	732.18	
1.2	461.40	674.20	
1.3	426.41	620.60	
1.4	394.01	571.02	
1.5	364.01	525.17	
1.6	336.23	482.75	
1.7	310.50	443.51	
1.8	286.67	407.21	
1.9	264.58	373.61	
2.0	244.12	342.51	
2.1	225.15	313.73	
2.2	207.57	287.09	
2.3	191.27	262.41	
2.4	176.15	239.57	
2.5	162.13	218.41	
2.6	149.12	198.81	
2.7	137.06	180.66	
2.8	125.86	163.84	
2.9	115.47	148.25	
3.0	105.82	133.80	
3.1	96.86	120.41	
3.2	88.54	108.00	
3.3	80.81	96.49	
3.4	73.63	85.81	
3.5	66.96	75.91	
3.6	60.76	66.73	
3.7	54.99	58.21	
3.8	49.63	50.30	
3.9	44.65	42.96	
4.0	40.01	36.15	
4.1	35.69	29.83	
4.2	31.68	23.95	
4.3	27.94	18.50	
4.4	24.46	13.43	
4.5	21.22	8.73	
4.6	18.20	4.36	
4.7	15.39	.29	
4.8	12.77	-3.49	
4.9	10.32	-7.00	
5.0	8.05	-10.26	
5.1	5.92	-13.30	
5.2	3.94	-16.13	
5.3	2.09	-18.76	
5.4	.36	-21.20	
5.5	-1.25	-23.48	
5.6	-2.76	-25.60	
5.7	-4.16	-27.57	
5.8	-5.47	-29.41	
5.9	-6.70	-31.12	
6.0	-7.85	-32.72	
6.1	-8.92	-34.20	
6.2	-9.93	-35.59	
6.3	-10.87	-36.88	

PROBLEM NO. 6--SAMPLE PROBLEM--TSI OPTION WITH 2 COMPARISONS

DISCOUNTED NET WORTH--SECOND TSI PLAN

RATE	ALT-PLAN 1 (ROTATION 80)	ALT-PLAN 2 (ROTATION 80)	ALT-PLAN 0 (ROTATION 0)
6.4	-11.75	-38.09	
6.5	-12.57	-39.21	
6.6	-13.34	-40.26	
6.7	-14.07	-41.24	
6.8	-14.74	-42.15	
6.9	-15.38	-43.01	
7.0	-15.97	-43.80	
7.1	-16.53	-44.55	
7.2	-17.05	-45.24	
7.3	-17.55	-45.89	
7.4	-18.01	-46.50	
7.5	-18.44	-47.07	
7.6	-18.85	-47.60	
7.7	-19.23	-48.09	
7.8	-19.59	-48.56	
7.9	-19.93	-49.00	
8.0	-20.25	-49.40	
8.1	-20.55	-49.78	
8.2	-20.83	-50.14	
8.3	-21.10	-50.48	
8.4	-21.35	-50.79	
8.5	-21.58	-51.09	
8.6	-21.81	-51.36	
8.7	-22.02	-51.62	
8.8	-22.21	-51.86	
8.9	-22.40	-52.09	
9.0	-22.58	-52.31	
9.1	-22.74	-52.51	
9.2	-22.90	-52.70	
9.3	-23.05	-52.88	
9.4	-23.19	-53.04	
9.5	-23.32	-53.20	
9.6	-23.45	-53.35	
9.7	-23.57	-53.49	
9.8	-23.68	-53.62	
9.9	-23.79	-53.74	
10.0	-23.89	-53.86	

PROBLEM NO. 6--SAMPLE PROBLEM--TSI OPTION WITH 2 COMPARISONS

DISCOUNTED NET WORTH OF ADDED TSI INVESTMENT

RATE	ALT-PLAN 1 (ROTATION 80)	ALT-PLAN 2 (ROTATION 80)	ALT-PLAN 0 (ROTATION 0)
1.0	390.32	645.15	
1.1	363.58	596.55	
1.2	338.54	551.34	
1.3	315.10	509.29	
1.4	293.16	470.17	
1.5	272.63	433.79	
1.6	253.42	399.94	
1.7	235.45	368.46	
1.8	218.64	339.18	
1.9	202.92	311.94	
2.0	188.22	286.61	
2.1	174.47	263.05	
2.2	161.61	241.13	
2.3	149.59	220.74	
2.4	138.35	201.77	
2.5	127.85	184.13	
2.6	118.03	167.72	
2.7	108.85	152.45	
2.8	100.26	138.24	
2.9	92.24	125.03	
3.0	84.74	112.73	
3.1	77.73	101.29	
3.2	71.18	90.64	
3.3	65.05	80.73	
3.4	59.33	71.51	
3.5	53.97	62.93	
3.6	48.97	54.94	
3.7	44.29	47.50	
3.8	39.91	40.58	
3.9	35.82	34.13	
4.0	31.99	28.13	
4.1	28.41	22.54	
4.2	25.06	17.34	
4.3	21.93	12.49	
4.4	19.00	7.97	
4.5	16.26	3.76	
4.6	13.69	-0.16	
4.7	11.29	-3.81	
4.8	9.04	-7.21	
4.9	6.94	-10.39	
5.0	4.97	-13.34	
5.1	3.12	-16.10	
5.2	1.39	-18.67	
5.3	-0.23	-21.07	
5.4	-1.74	-23.31	
5.5	-3.16	-25.39	
5.6	-4.50	-27.34	
5.7	-5.75	-29.16	
5.8	-6.92	-30.85	
5.9	-8.01	-32.43	
6.0	-9.04	-33.91	
6.1	-10.01	-35.29	
6.2	-10.92	-36.58	
6.3	-11.77	-37.78	

PROBLEM NO. 6--SAMPLE PROBLEM--TSI OPTION WITH 2 COMPARISONS

DISCOUNTED NET WORTH OF ADDED TSI INVESTMENT

RATE	ALT-PLAN 1 (ROTATION 80)	ALT-PLAN 2 (ROTATION 80)	ALT-PLAN 0 (ROTATION 0)
6.4	-12.57	-38.91	
6.5	-13.32	-39.96	
6.6	-14.02	-40.94	
6.7	-14.68	-41.86	
6.8	-15.31	-42.72	
6.9	-15.89	-43.52	
7.0	-16.44	-44.27	
7.1	-16.96	-44.97	
7.2	-17.44	-45.63	
7.3	-17.90	-46.24	
7.4	-18.33	-46.82	
7.5	-18.73	-47.36	
7.6	-19.12	-47.86	
7.7	-19.48	-48.34	
7.8	-19.81	-48.78	
7.9	-20.13	-49.20	
8.0	-20.43	-49.59	
8.1	-20.72	-49.95	
8.2	-20.98	-50.30	
8.3	-21.24	-50.62	
8.4	-21.47	-50.92	
8.5	-21.70	-51.20	
8.6	-21.91	-51.47	
8.7	-22.11	-51.72	
8.8	-22.30	-51.95	
8.9	-22.48	-52.17	
9.0	-22.65	-52.38	
9.1	-22.81	-52.58	
9.2	-22.96	-52.76	
9.3	-23.11	-52.93	
9.4	-23.24	-53.09	
9.5	-23.37	-53.25	
9.6	-23.49	-53.39	
9.7	-23.61	-53.53	
9.8	-23.72	-53.65	
9.9	-23.82	-53.77	
10.0	-23.92	-53.89	

APPENDIX

INVESTMENT ANALYSIS PROGRAM NO. 6

This program is a modification of the program prepared originally by Clark Row[9] and later revised by Robert Marty et al.[10] The basic changes made in this version of the program are as follows:

1. Change in input requirements so that periodic and annual incomes can be handled in addition to periodic and annual costs. Cost items are identified in the input with a minus sign (-) preceding the amount of the cost. Final value, treated as a separate item in the original program, is handled as a periodic income in this version of the program.

2. Change in input requirements so that the program can be used with and without product evaluations. That is, if only periodic costs and incomes are involved, the only control cards needed are those associated with periodic costs. If both periodic and annual costs and incomes are included in the problem, only those control cards associated with periodic and annual costs and incomes are required. If product evaluations are included in the problem, additional control cards are required.

3. Addition of an option for evaluating timber stand replacement priorities. This option requires two sets of control cards: one set shows costs and incomes associated with the future timber growing opportunity; a second set shows costs and incomes associated with the present stand conversion opportunity. The future timber growing opportunity and the present stand conversion opportunity are evaluated separately and then together.

4. Addition of an option for evaluating timber stand improvement (TSI) programs. This option is used to evaluate timber stand improvement program levels and is particularly useful where the program differences to be evaluated affect the yield in a complex way. For example, the inclusion of thinning in the timber growing program may affect the quality, quantity, and timing of intermediate cuts as well as the final cut.

Two sets of control cards are used: one describes the minimum program considered, and a second describes the program with one or more other timber practices included. Each of the programs is evaluated separately and then the effect of the practices added is evaluated.

INPUT REQUIREMENTS IN BRIEF

Up to 15 different cards or card types (groups of repeated cards) are used, depending on the nature of the problem and the way the program is being used. Whenever the program is used to evaluate stand replacement or timber stand improvement programs, cards or card types 7 through 13 are repeated as needed to form the second set of control cards mentioned above.

These 15 different cards or card types may also be grouped into four classes.

CLASS I includes cards 1, 2, and 3. These are used to identify the program user and are required only with the first problem when a user is submitting a number of problems.

CLASS II includes cards 4, 6, and 7 (and 5 where used), which are problem descriptions and general control cards required with every problem.

[9] *Row, Clark. Determining forest investment rates of return by electronic computer. U.S. Forest Serv. Res. Pap. SO-6, 13 pp. 1963.*

[10] *Marty, Robert, Charles Rendt, and John Fedkiw. A guide for evaluating reforestation and stand improvement projects in timber management on the National Forests. U.S. Dep. Agr., Agr. Handbook 304, 24 pp. 1966.*

CLASS III includes cards or card types 8, 9, 10, 11, 12, and 13. These are used only as needed to enter cost, income, product, and price information.

CLASS IV includes cards 14 and 15, which are problem termination cards. Card 14 is always required. Card 15 is required when the problem of another user is to be entered.

CONTROL CARD FUNCTIONS

Class I Cards

(Required with the first problem in each series of problems submitted)

Card 1. Name of National Forest or organization. – This card, with cards 2 and 3, puts the name of the user and his organization into the computer so that they can be printed on the output to facilitate identification and handling.

Card 2. Name of unit or branch.

Card 3. Name of user.

Class II Cards

(Required for every problem)

Card 4. Number and/or name of problem and number of descriptive cards. – This card puts the problem identification into the computer for use as a label on output information.

Card 5. This card type is used to put into the computer additional descriptive information that the user wants to have on the output. – For example, if two or more alternatives are being compared, the user may wish to include a description of each alternative on the computer output.

Card 6. Interest rates and program and output options. – This program utilizes the iteration procedure of calculation; that is, the user specifies the minimum and maximum interest rates he will consider, and the increment of change the computer is to use. Also the program permits three options:

1. A general option for computing internal rate of return and present worth at specified interest rates.
2. An option to evaluate timber stand replacement opportunities.
3. An option to evaluate timber stand improvement opportunities.

The above are specified on the 6th card.

Card 7. General problem control card. – This card describes the details of the problem to the computer. Nine types of information are included on this card:

1. The number of alternatives or plans to be evaluated. The program will handle up to six alternatives or plans at once, provided they utilize the same program and output options (specified on card 6). This information type tells the computer how many alternatives or plans are included in the problem.
2. Numbers identifying each alternative or plan to be evaluated.
3. The time period (rotation) specified for each plan.
4. If product evaluations are included, the maximum number of products (0-3) in any alternative or plan for which dollar yield must be figured.
5. If periodic costs and incomes are included, the maximum number and the number in each plan or alternative.
6. If annual costs are included, the maximum number and the number in each plan or alternative.
7. The type of terminal calculation the computer is to use for each plan or alternative (that is, a perpetual series or a terminating series).
8. More specific instructions if the problem involves the evaluation of stand replacement or a comparison of TSI programs.
9. The number of sets of product prices, if product evaluations are included in the problem, so that the problem can be repeated under all the price assumptions specified.

Class III Cards

(Used only as needed)

Card 8. Periodic costs and incomes. – This *card type* is used whenever periodic costs and

incomes are included in any of the alternatives or plans in the problem, and it can be repeated as many times as needed (maximum 99) to include all periodic costs and incomes. In order to minimize the number of cards required, one periodic cost or income for each of the six possible alternatives or plans can be entered on each card. A periodic cost or income for alternative or plan 1 is entered first on the card, followed in order by one each for alternatives or plans 2, 3, 4, 5, and 6.

Card 9. Annual costs and incomes. – This *card type* is used whenever annual costs and incomes are included in any of the alternatives or plans in the problem. One card is required for each alternative or plan in which annual costs or incomes are included, and four annual costs or incomes for the particular alternative or plan can be entered on the card.

Card 10. Product evaluation control card. – This card and card types 11, 12, and 13 are used only when product evaluations are included in any of the alternatives or plans in the problem. This specific card gives the computer the following information:

1. The maximum number of product 1 returns in any alternative or plan as well as the number in each specific alternative or plan.
2. The maximum number of product 2 returns in any alternative or plan as well as the specific number in each alternative or plan.
3. The maximum number of product 3 returns in any alternative or plan as well as the specific number in each alternative or plan.

Card 11. Product names and units of measure. – This card gives the computer the names and units of measure of each product.

Card 12. Product yields. – This *card type* is used to feed product yield information into the computer; it can be repeated as necessary (maximum 99) to include all yield data. It gives the computer the year the product is harvested, and the volume and quality harvested; the product is identified from the order in which the cards are entered. Product 1 cards are entered first, followed by the cards for products 2 and 3. To minimize the number of cards required, data describing one yield for each of the six possible alternatives or plans is entered on each card *provided the data applies to the same product.* This information is entered in the same order described for card type 8.

Card 13. Product prices. – This *card type* is for feeding product price information into the computer. Each card contains a set of product prices, one for each product. Also, it gives the rate at which each product price is expected to change with time (if the rate is constant). If the problem is to be evaluated under a number of different price assumptions (maximum 9), this card can be repeated. The number of times it will be repeated is that specified in the last entry on card 7.

Class IV Cards

(Card 14 required, card 15 as needed)

Card 14. Problem termination card. – This card is required with every problem. It tells the computer if (1) another problem by the same user follows, (2) a problem by another user follows (card 15 is to be read), or (3) this is the last problem by this user and no other problems follow.

Card 15. NEW USER card. – This card is used *only* when a problem of another user follows. It signals the computer to read cards 1, 2, and 3 for the new user's location and identity.

INSTRUCTIONS FOR PREPARING CONTROL CARDS
INVESTMENT PROGRAM NO. 6

Card	Columns	Item	Field	Label
1	1-20	Name of Forest or organization		NAME
2	1-20	Name of unit		
3	1-20	Name of user		
4	1-76	Number and/or name of problem		
	79-80	Number of description cards (when used)	XX	ID
5	1-80	Problem description		IDEN
6	1-4	Minimum rate of interest to be considered	.XXX	RINT
	5-8	Interest rate increment	.XXX	
	9-12	Maximum rate of interest to be considered	.XXX	
	13-14	Program options 01 = General evaluation of alternatives – Computation of internal rate of return and present worth 02 = Evaluation of stand replacement alternatives 03 = For TSI planning – Computation of internal rate of return and present worth for programs compared and differences between them	XX	JPR
7	1-2	Number of alternatives or plans	XX	LX
	3-4	Number identifying alternative or plan 1	XX	LI(L)
	5-6	Number identifying alternative or plan 2	XX	
	7-8	Number identifying alternative or plan 3	XX	
	9-10	Number identifying alternative or plan 4	XX	
	11-12	Number identifying alternative or plan 5	XX	
	13-14	Number identifying alternative or plan 6	XX	
	15-17	Time period, alternative or plan 1	XXX	LY(L)
	18-20	Time period, alternative or plan 2	XXX	
	21-23	Time period, alternative or plan 3	XXX	
	24-26	Time period, alternative or plan 4	XXX	
	27-29	Time period, alternative or plan 5	XXX	
	30-32	Time period, alternative or plan 6	XXX	
	33-34	Maximum number of products in any alternative or plan (0-3)	XX	KX
	35-36	Maximum number of periodic costs or incomes in any alternative or plan	XX	KCXX

Card	Columns	Item	Field	Label
	37-38	Number of periodic costs or incomes, alternative or plan 1	XX	KCX(L)
	39-40	Number of periodic costs or incomes, alternative or plan 2	XX	
	41-42	Number of periodic costs or incomes, alternative or plan 3	XX	
	43-44	Number of periodic costs or incomes, alternative or plan 4	XX	
	45-46	Number of periodic costs or incomes, alternative or plan 5	XX	
	47-48	Number of periodic costs or incomes, alternative or plan 6	XX	
	49-50	Maximum number of annual costs or incomes in any alternative or plan	XX	JXX
	51-52	Number of annual costs or incomes, alternative or plan 1	XX	JX(L)
	53-54	Number of annual costs or incomes, alternative or plan 2	XX	
	55-56	Number of annual costs or incomes, alternative or plan 3	XX	
	57-58	Number of annual costs or incomes, alternative or plan 4	XX	
	59-60	Number of annual costs or incomes, alternative or plan 5	XX	
	61-62	Number of annual costs or incomes, alternative or plan 6	XX	
	63-64	Type of terminal calculation 00 = perpetual series for all alternatives or plans 01 = terminating series for at least 1 alternative or plan	XX	NZZ
	65-66	Type of terminal calculation, alternative or plan 1 00 = perpetual series 01 = terminating series	XX	NZ(L)
	67-68	Type of terminal calculation, alternative or plan 2	XX	
	69-70	Type of terminal calculation, alternative or plan 3	XX	
	71-72	Type of terminal calculation, alternative or plan 4	XX	

Card	Columns	Item	Field	Label
	73-74	Type of terminal calculation, alternative or plan 5	XX	
	75-76	Type of terminal calculation, alternative or plan 6	XX	
	77-78	Used only with program options 2 and 3 Option 2 01 = future stands 02 = present stands Option 3 01 = initial plan 02 = second TSI plan	XX	ISI
	79-80	Number of sets of product prices (0-9)	XX	MX
8		(This card is used where KCXX (columns 35-36 on card 7) is greater than 00; it is for listing periodic costs and incomes. One cost or income for each of 6 alternatives or plans can be entered on each card. Card can be repeated 99 times. All cost items are preceded by a minus sign (-).)		
	1-3	Year of i^{th} cost or income, alternative or plan 1	XXX	NC(L,KC)
	4-12	Amount of i^{th} cost or income, alternative or plan 1	XXXXXX.XX	PLCO(L,KC)
	13-15	Year of i^{th} cost or income, alternative or plan 2	XXX	
	16-24	Amount of i^{th} cost or income, alternative or plan 2	XXXXXX.XX	
	25-27	Year of i^{th} cost or income, alternative or plan 3	XXX	
	28-36	Amount of i^{th} cost or income, alternative or plan 3	XXXXXX.XX	
	37-39	Year of i^{th} cost or income, alternative or plan 4	XXX	
	40-48	Amount of i^{th} cost or income, alternative or plan 4	XXXXXX.XX	
	49-51	Year of i^{th} cost or income, alternative or plan 5	XXX	
	52-60	Amount of i^{th} cost or income, alternative or plan 5	XXXXXX.XX	
	61-63	Year of i^{th} cost or income, alternative or plan 6	XXX	
	64-72	Amount of i^{th} cost or income, alternative or plan 6	XXXXXX.XX	

Card	Columns	Item	Field	Label
9		(This card is used when JXX (columns 49-50 on card 7) is greater than 00; it is for listing annual costs or incomes. As many as 4 annual costs or incomes for an alternative or plan can be listed on 1 card. The limit is 1 card for each alternative. All cost items are preceded by a minus sign (-).)		
	1-3	Starting year of 1st annual item	XXX	NI(J)
	4-6	Terminating year of 1st annual item	XXX	NT(J)
	7-14	Amount of 1st annual item	XXXXX.XX	AN(II,J)
	15-20	Change in 1st annual item (If change is a decrease, a minus sign (-) precedes the amount)	XX.XXX	CAN(II,J)
	21-23	Starting year of 2nd annual item	XXX	
	24-26	Terminating year of 2nd annual item	XXX	
	27-34	Amount of 2nd annual item	XXXXX.XX	
	35-40	Change in 2nd annual item	XX.XXX	
	41-43	Starting year of 3rd annual item	XXX	
	44-46	Terminating year of 3rd annual item	XXX	
	47-54	Amount of 3rd annual item	XXXXX.XX	
	55-60	Change in 3rd annual item	XX.XXX	
	61-63	Starting year of 4th annual item	XXX	
	64-66	Terminating year of 4th annual item	XXX	
	67-74	Amount of 4th annual item	XXXXX.XX	
	75-80	Change in 4th annual item	XX.XXX	
		(Cards 10, 11, 12, and 13 are used only when product values are to be computed – KX (columns 33-34 on card 7) is greater than 00.)		
10	1-2	Maximum number of product 1 returns in any alternative or plan	XX	K1XX
	3-4	Number of product 1 returns, alternative or plan 1	XX	K1X(L)
	5-6	Number of product 1 returns, alternative or plan 2	XX	
	7-8	Number of product 1 returns, alternative or plan 3	XX	
	9-10	Number of product 1 returns, alternative or plan 4	XX	
	11-12	Number of product 1 returns, alternative or plan 5	XX	
	13-14	Number of product 1 returns, alternative or plan 6	XX	

Card	Columns	Item	Field	Label
	15-16	Maximum number of product 2 returns in any alternative or plan	XX	K2XX
	17-18	Number of product 2 returns, alternative or plan 1	XX	K2X(L)
	19-20	Number of product 2 returns, alternative or plan 2	XX	
	21-22	Number of product 2 returns, alternative or plan 3	XX	
	23-24	Number of product 2 returns, alternative or plan 4	XX	
	25-26	Number of product 2 returns, alternative or plan 5	XX	
	27-28	Number of product 2 returns, alternative or plan 6	XX	
	29-30	Maximum number of product 3 returns in any alternative or plan	XX	K3XX
	31-32	Number of product 3 returns, alternative or plan 1	XX	K3X(L)
	33-34	Number of product 3 returns, alternative or plan 2	XX	
	35-36	Number of product 3 returns, alternative or plan 3	XX	
	37-38	Number of product 3 returns, alternative or plan 4	XX	
	39-40	Number of product 3 returns, alternative or plan 5	XX	
	41-42	Number of product 3 returns, alternative or plan 6	XX	
11	1-20	Name and unit of measure, product 1		A
	21-40	Name and unit of measure, product 2		
	41-60	Name and unit of measure, product 3		
12	1-3	Year of j^{th} return, k^{th} product, alternative or plan 1	XXX	N1(L,K1)
	4-8	Volume of j^{th} yield, k^{th} product, alternative or plan 1	XXXXX[11]	JLD1(L,K1)
	9-12	Quality index, j^{th} yield, k^{th} product, alternative or plan 1	XXXX[12]	JUAL1(L,K1)

[11] *Decimal implied before last digit (127.3 punches 01273).*

[12] *Decimal implied before 3rd digit (1.15 punches 0115).*

Card	Columns	Item	Field	Label
	13-15	Year of j^{th} return, k^{th} product, alternative or plan 2	XXX	N2(L,K2)
	16-20	Volume of j^{th} yield, k^{th} product, alternative or plan 2	XXXXX[11]	JLD2(L,K2)
	21-24	Quality of j^{th} yield, k^{th} product, alternative or plan 2	XXXX[12]	JUAL2(L,K2)
	25-27	Year of j^{th} return, k^{th} product, alternative or plan 3	XXX	N3(L,K3)
	28-32	Volume of j^{th} yield, k^{th} product, alternative or plan 3	XXXXX[11]	JLD3(L,K3)
	33-36	Quality of j^{th} yield, k^{th} product, alternative or plan 3	XXXX[12]	JUAL3(L,K3)
	37-39	Year of j^{th} return, k^{th} product, alternative or plan 4	XXX	N4(L,K4)
	40-44	Volume of j^{th} return, k^{th} product, alternative or plan 4	XXXXX[11]	JLD4(L,K4)
	45-48	Quality of j^{th} return, k^{th} product, alternative or plan 4	XXXX[12]	JUAL4(L,K4)
	49-51	Year of j^{th} return, k^{th} product, alternative or plan 5	XXX	N5(L,K5)
	52-56	Volume of j^{th} return, k^{th} product, alternative or plan 5	XXXXX[11]	JLD5(L,K5)
	57-60	Quality of j^{th} return, k^{th} product, alternative or plan 5	XXXX[12]	JUAL5(L,K5)
	61-63	Year of j^{th} return, k^{th} product, alternative or plan 6	XXX	N6(L,K6)
	64-68	Volume of j^{th} return, k^{th} product, alternative or plan 6	XXXXX[11]	JLD6(L,K6)
	69-72	Quality of j^{th} return, k^{th} product, alternative or plan 6	XXXX[12]	JUAL6(L,K6)
	(Card 12 may be repeated 49 times if necessary to include all product returns.)			
13	1-9	i^{th} unit price assumption, product 1	XXXXX.XXX	PR1(M)
	10-18	i^{th} change in unit price, product 1	XXXXX.XXX	CPR1(M)
	19-27	i^{th} unit price assumption, product 2	XXXXX.XXX	PR2(M)
	28-36	i^{th} change in unit price, product 2	XXXXX.XXX	CPR2(M)
	37-45	i^{th} unit price assumption, product 3	XXXXX.XXX	PR3(M)

[11] *Decimal implied before last digit (127.3 punches 01273).*

[12] *Decimal implied before 3rd digit (1.15 punches 0115).*

Card	Columns	Item	Field	Label
	46-54	i^{th} change in unit price, product 3	XXXXX.XXX	CPK3(M)
	(Card 13 may be repeated 8 times if additional price assumptions are needed.)			
14	1-2	Terminal (punch 98 or 99) Punch 98 if another problem follows Punch 99 if last problem		
15	1-10	NEW FOREST – **used only** if problem that follows is from a new user		

SAMPLE PROBLEMS

Following are seven sample problems prepared as input by a single user. The data input forms for the seven problems are shown in figures 7-13.

Problem 1 illustrates use of the general evaluation option with two alternatives or plans in which only periodic costs and incomes are involved.

Problem 2 again illustrates the general option but with periodic and annual costs and incomes. The problem is treated first as a perpetuated series and second as a terminating series.

Problem 3 is the same as problem 1 but the job of figuring product yields is left to the computer.

Problem 4 illustrates use of the stand replacement option. The problem here is to evaluate the financial advantage of cutting a stand now over holding it another 10 years.

Problem 5 is another illustration of the stand replacement option, but this time two stands are compared.

Problem 6 illustrates use of the timber stand improvement (TSI) program option. Two comparisons are made: In the first a plan calling for no TSI work is compared with a plan including thinning, and in the second, a plan calling for no TSI work is compared with a plan calling for pruning in addition to thinning.

Problem 7 illustrates use of the program in timber sale planning.

A Word About the Input

Problem 1. Note that in addition to user identification and problem title and description, only seven cards are required – one card giving interest rate and program and output specifications, one card for general program control data, and five cards for periodic cost and income data.

Problem 2. This problem contains both periodic and annual costs and incomes. It requires the same type of input as problem 1 except that nine cards are required to enter all the periodic cost and income information and two cards are required to enter the annual costs.

Problem 3. This problem utilizes the product evaluation option and requires a product option control card, a card identifying the product and unit of measure, six cards to feed in product data, and a card giving product price. Note that the product control card specifies a maximum of six products, with six in alternative or plan 1 and four in alternative or plan 2. Note also that product price is expected to increase at the rate of .005 percent per year.

Problem 4. This problem, which utilizes the stand replacement option, requires one set of cards describing the future timber growing opportunity and a second set describing the present stand conversion opportunity. In this problem, which is to evaluate the financial advantage of cutting a stand now or holding it another 10 years, the future timber growing opportunity is assumed to be the same in

both cases. The second set of cards (beginning with card or card type 6 in the classification given earlier) contains the cost and income data for the present crop. In this problem it is assumed that all development is accomplished, so only the product evaluation option is utilized in the second card set. Note that in this problem the future timber growing opportunity is evaluated as a perpetual series, whereas the present stand conversion opportunity is terminated.

Problem 5. In this problem (stand replacement) two areas are compared to see which offers the best stand conversion and timber growing opportunity. One is a relatively poor piece of land supporting a stand that contains 7,400 cubic feet of usable wood. The other is an area of good land supporting a highly defective overmature stand of less usable volume.

Problem 6. This problem looks into a TSI program. In this problem even if the manager does nothing in the way of cultural work he expects a certain result. He could thin, but he needs to know what the result would be in terms of return on the thinning investment. Or, he could thin and prune. Under alternative or plan 1, thinning is compared with no cultural work. Under alternative or plan 2, a program of thinning and pruning is compared with a program involving no cultural work. Again, two card sets are required, one for each set of management assumptions being compared under the two alternatives or plans.

Problem 7. This problem is a comparison of four timber growing alternatives on a proposed sale area made in conjunction with silvicultural planning for the area. The proposed sale is on a good site capable of producing a harvest yield of 35,000 board feet per acre in 55 years or 70,000 board feet in 85 years with stocking control. Comparisons are made using both 55- and 85-year rotations.

Plan 1. Leave one seed tree group averaging one-fourth acre in size and containing 10 Mbf for every 5 acres cut. Seed tree losses in slash disposal and site preparation are expected to be 20 percent. The per-acre cost of added work required to protect seed trees in slash disposal and site preparation is estimated to be $10.00.

Plan 2. Clearcut and plant following slash disposal, with planting expected to be necessary on half the area.

Plan 3. Clearcut with natural regeneration. This plan assumes a good seed year prior to cutting.

Plan 4. Clearcut and seed, with seeding expected to be necessary on half the area.

The costs used in this problem are shown in table 5. The yields expected are shown in table 6.

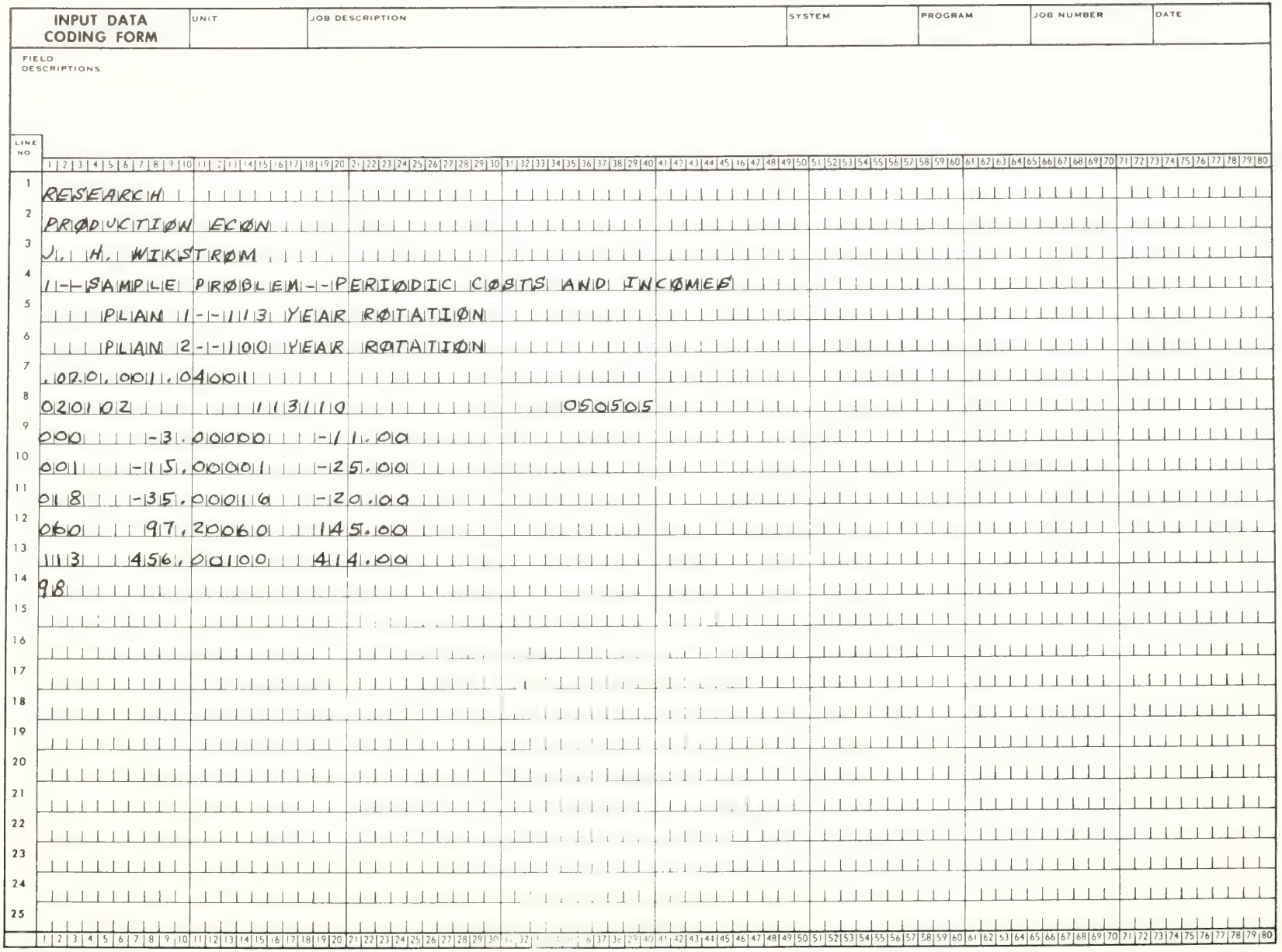
Table 5. — Average costs per acre for the problem area as a whole according to activity and plan

Activity	Plan 1	Plan 2	Plan 3	Plan 4
		Dollars		
Site preparation	10.00			
Value of seed trees	20.00			
Cost of seed tree salvage sale	.40			
Cost of seed tree sale	4.00			
Planting		19.00		
Seeding				9.00
Thinning	25.00	15.00	25.00	22.00
Stage 2 surveys	.50	.50	.50	.50

Table 6. — Expected yields per acre according to type of cut and plan

Type of cut	Plan 1	Plan 2	Plan 3	Plan 4
		Thousand board feet		
Seed tree salvage	.4			
Seed tree harvest	1.6			
Harvest at age 55	28.0	35.0	31.0	31.0
Intermediate cut at age 50	8.0	10.0	9.0	9.0
Harvest cut at age 85	65.0	70.0	68.0	68.0

Figure 7. – Computer input, Problem 1.



INPUT DATA CODING FORM | UNIT | JOB DESCRIPTION | SYSTEM | PROGRAM | JOB NUMBER | DATE

FIELD DESCRIPTIONS

LINE NO

```
1  RESEARCH
2  PRODUCTION ECON
3  J. H. WICKSTROM
4  1--SAMPLE PROBLEM--PERIODIC COSTS AND INCOMES
5      PLAN 1--1113 YEAR ROTATION
6      PLAN 2--1010 YEAR ROTATION
7  .02.01.001.04001
8  02010Z      1131110          0505050
9  000    -3.00000    -1 1.00
10 001    -115.00001    -25.101
11 018    -35.00016    -20.00
12 060    97.200610    145.100
13 1113   456.01010    4141.00
14 98
15
16
17
18
19
20
21
22
23
24
25
```

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Figure 8. – Computer input, Problem 2.

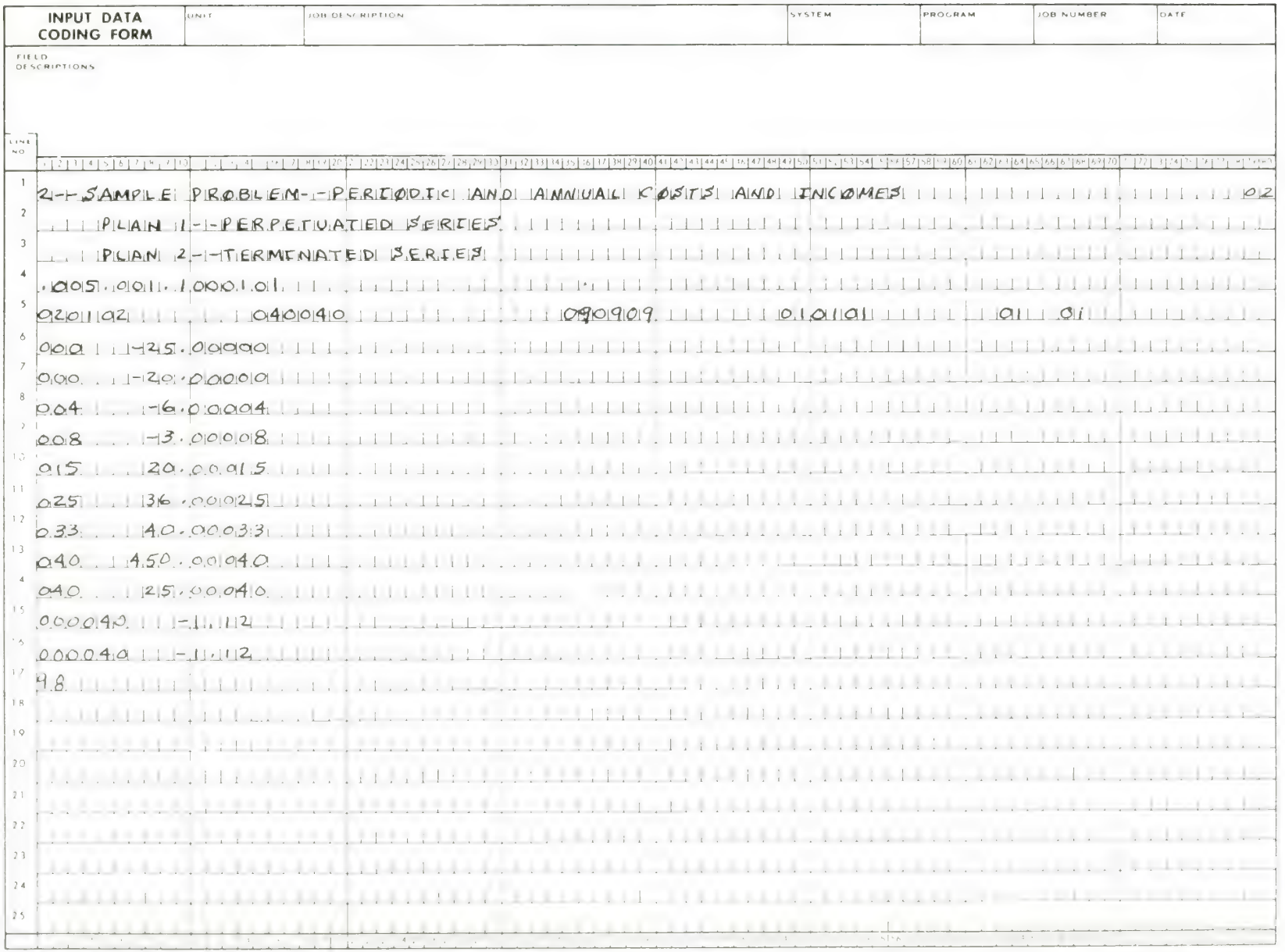

Figure 9. – Computer input, Problem 3.

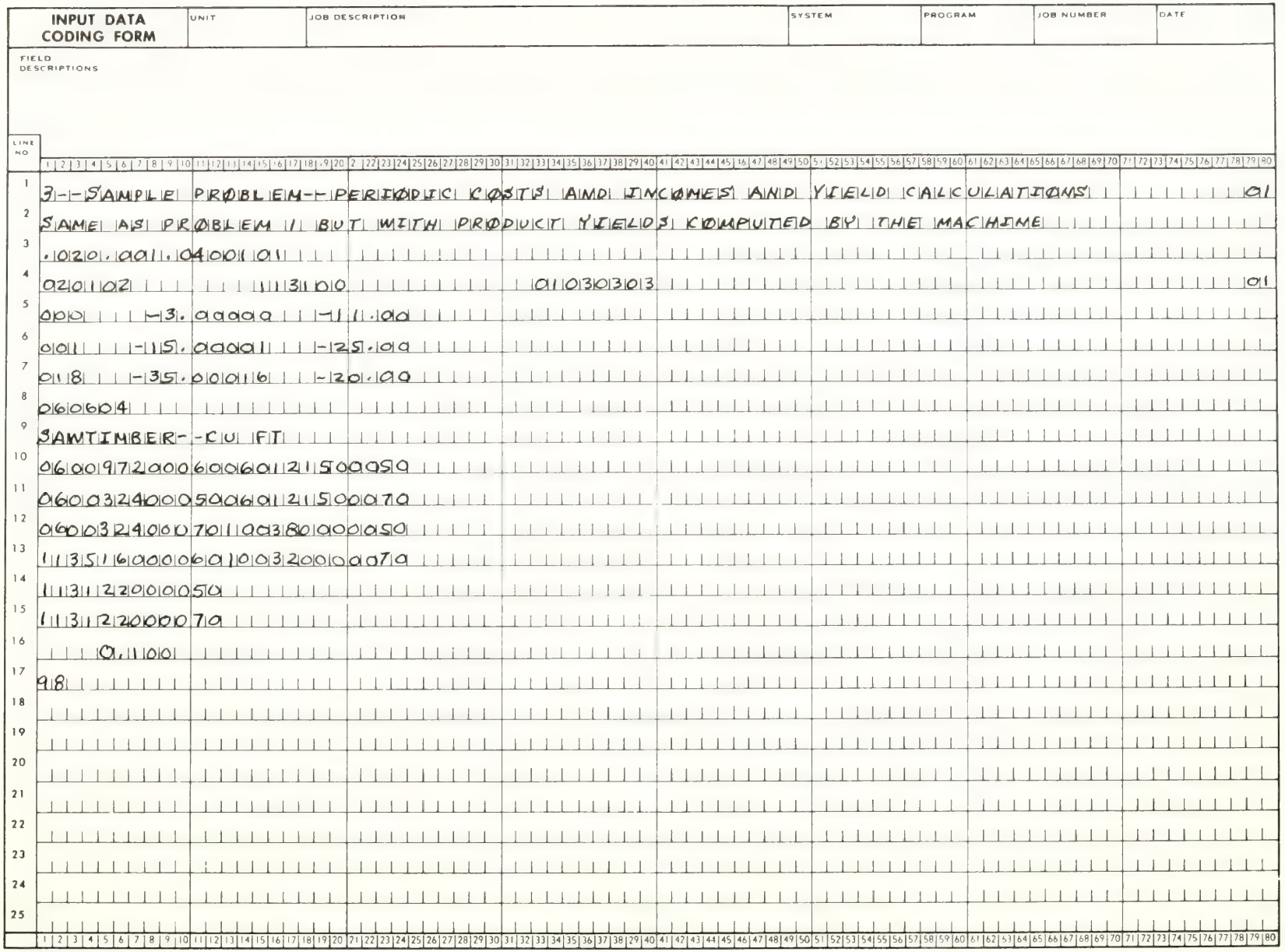

Figure 10. — Computer input, Problem 4.

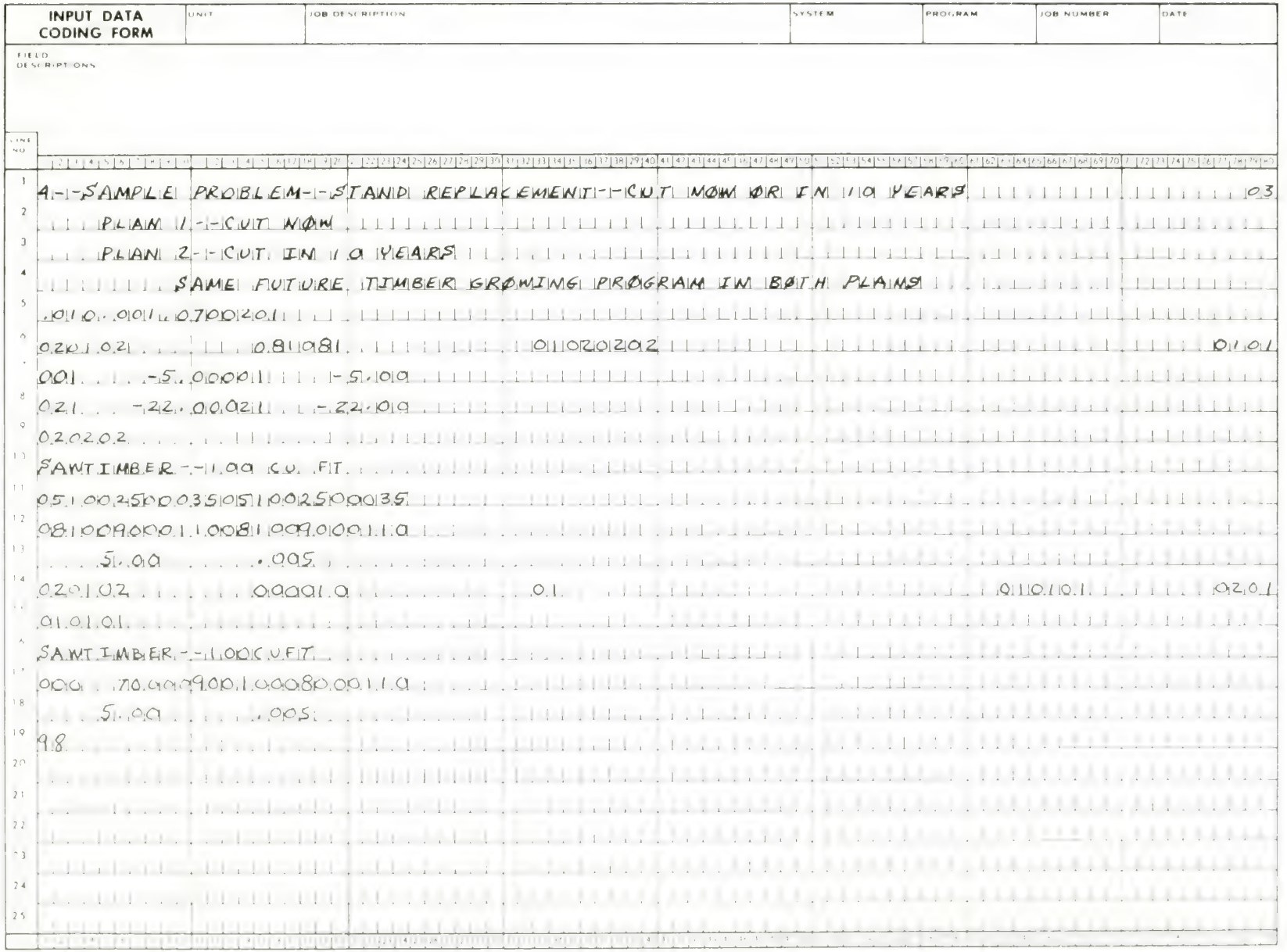

Figure 11. – Computer input, Problem 5.

INPUT DATA CODING FORM	UNIT	JOB DESCRIPTION	SYSTEM	PROGRAM	JOB NUMBER	DATE

FIELD DESCRIPTIONS

LINE NO	
1	5--SAMPLE PROBLEM--STAND REPLACEMENT--COMPARISON OF 2 STANDS
2	PLAN 1--CUT HIGHEST VOLUME STAND ON POOR LAND
3	PLAN 2--CUT LOW VOLUME STAND ON GOOD LAND
4	.01 0.001. 100201
5	02 03 07 10081 01 01 01 01 01 01
6	030 -125. 000115 -125.00
7	02 02 02
8	SAWTIMBER--100 CU FT
9	075. 200 35050 300 50
10	110. 800 900081 2010 140
11	7.100 .005
12	02 03 07 10030 03 01 02 02 02 01 01 01 01 02 01
13	001 -7. 00001 -6.00
14	002 -124. 00002 -22.00
15	01 01 01
16	SAWTIMBER--100 CU FT
17	003 7140 900003 5910 910
18	7.00 .005
19	98
20	
21	
22	
23	
24	
25	

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Figure 12.—Computer input, Problem 6.

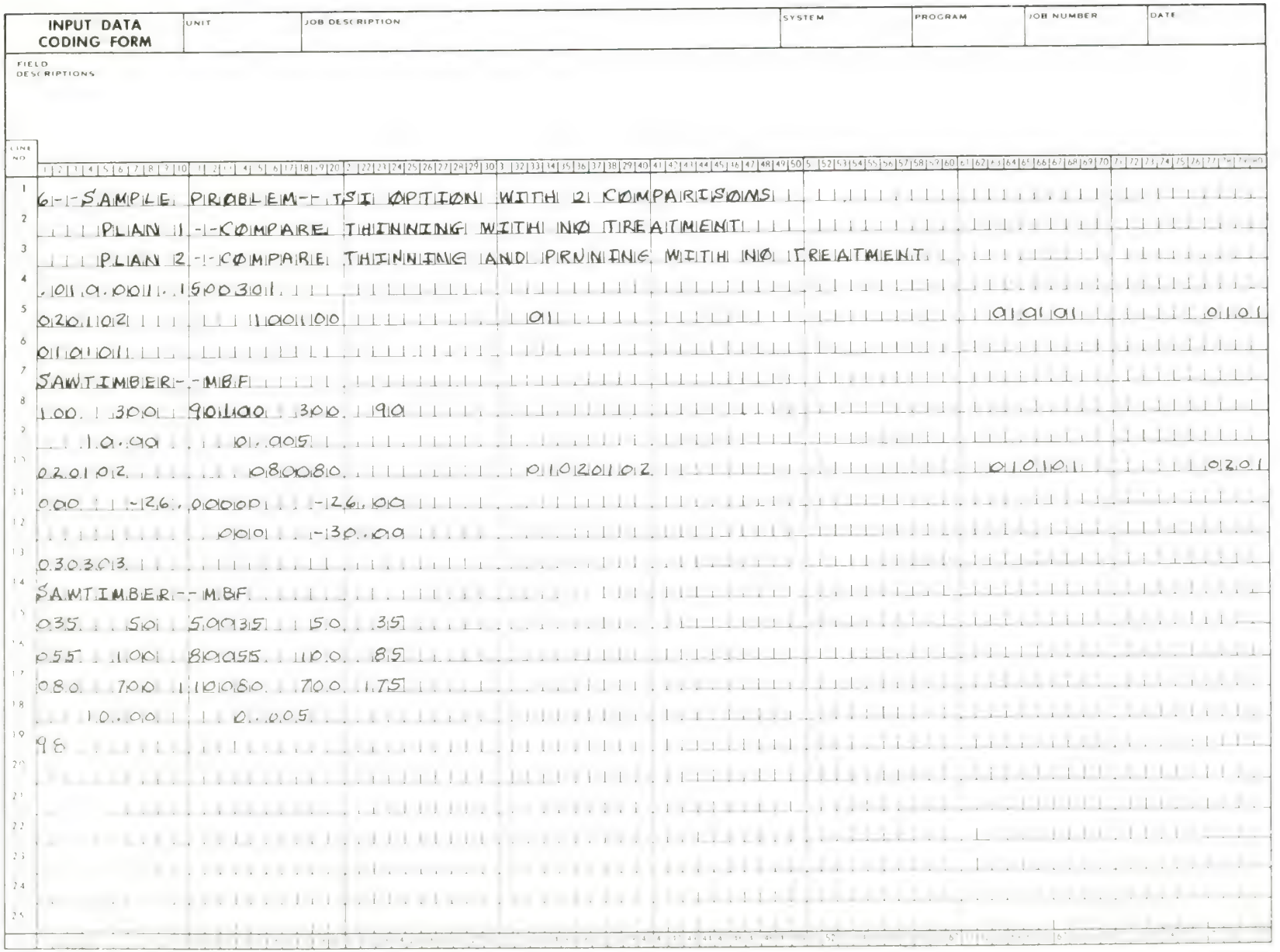
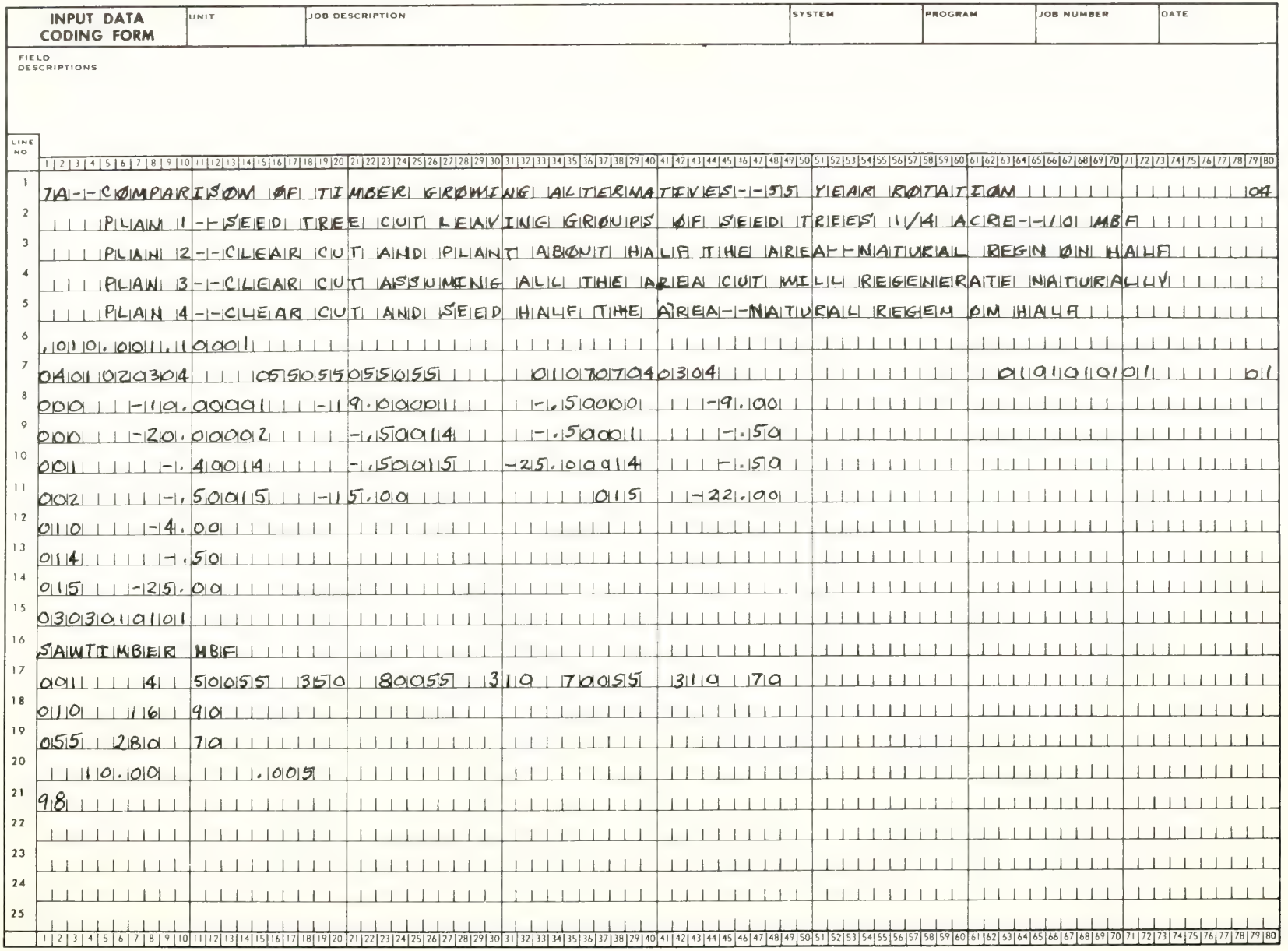


Figure 13. – Computer input, Problem 7.



INPUT DATA CODING FORM | UNIT | JOB DESCRIPTION | SYSTEM | PROGRAM | JOB NUMBER | DATE

FIELD DESCRIPTIONS

LINE NO	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
1	7	A	-	-	C	O	M	P	A	R	I	S	O	N		O	F		T	I	M	B	E	R		G	R	O	W	I	N	G		A	L	T	E	R	N	A	T	I	V	E	S	-	-	S	S		Y	E	A	R		R	O	T	A	T	I	O	N																										O	R
2				P	L	A	I	N		1	-	-	S	E	E	D		T	R	E	E		C	U	T		L	E	A	V	I	N	G		G	R	O	U	P	S		O	F		S	E	E	D		T	R	E	E	S		1	1	/	4		A	C	R	E	-	-	1	/	0		M	B	F																		

INPUT DATA CODING FORM	UNIT	JOB DESCRIPTION	SYSTEM	PROGRAM	JOB NUMBER	DATE

FIELD DESCRIPTIONS

```
LINE NO
1  7B COMPARISON OF TIMBER GROWING ALTERNATIVES--85 YEAR ROTATION
2  .01|9.|0|0|1.|1|0|0|0|1
3  0|4|0|1|0|2|0|3|0|4          085|085|085          10|10|70|70|4|0|13|0|4|9          10|10|10|10|10|11
4  0|0|0          -1|1|0.|0|0|0|1          -1|9.|0|0|0|1          -1.|5|0|0|0|0          -9|1.|0|0
5  0|0|0          -1|2|0.|0|0|0|2          -1.|5|0|0|1|4          -1.|5|0|0|0|1          -1.|5|0
6  0|0|1          -1|4|0|0|1|4          -1.|5|0|0|1|5          -2|5|.|0|0|0|1|4          -1.|5|0
7  0|0|2          -1.|5|0|0|1|5          -1|5.|0|0          10|1|5          -2|2.|0|0
8  0|1|0          -4|.|0|0
9  0|1|4          -1.|5|0
10 0|1|5          -2|5.|0|0
11 0|A|0|4|0|2|0|2|0|2
12 S|A|W|T|I|M|B|E|R          M|B|F
13 0|0|1          4          5|0|0|5|0          1|0|0          6|0|0|5|0|1          9|0          5|0|0|5|0|1          9|0          1|5|0
14 0|1|0          1|6          9|0|0|8|5          7|0|0          1|0|0|0|8|5          6|8|0          9|5|0|8|5          6|8|0          9|5
15 0|5|0          8|0          5|0
16 0|8|5          6|5|0          9|5
17          1|0.|0|0          .|0|0|5
18 9|9
19
20
21
22
23
24
25
```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A Word About the Output

The computer output for the seven problems is shown in figures 14-20. Note that all the input is printed on the output. Control cards 6 and 7, and 11 when used, are labeled along with the information they contain. This is to facilitate the search for errors in input should any occur. Thus, when KX (control card 7) is greater than 0, product evaluations are to be made. If KX is 0 and product control cards are included in the problem, an error message results and the computer aborts the problem.

When KCXX (control card 7) is greater than 0, periodic costs and incomes are read. The number under each of the six KCX's indicates the number of periodic costs and incomes included in each of the six alternatives or plans that can be read simultaneously.

When JXX (control card 7) is greater than 0, annual costs and incomes are read. The number under each of the six JX's indicates the number of annual costs and incomes to be read in each of the six possible alternatives or plans.

When NZZ is greater than 0 (it will be either 0 or 1), at least one of the alternatives or plans is to be treated as a terminated series. A 0 or 1 under the JX's indicates how each of the six possible alternatives or plans is to be evaluated:

0 = perpetual series

1 = terminated series

The IST is used only with program options 2 and 3 to indicate which evaluation is to be made. It is coded 1 on the first card set, and 2 on the second.

When KX is greater than 0, MX (control card 7) must also be greater than 0. MX indicates the number of price assumptions to be read. If MX is 2, there must be two cards of card type 13.

General option output. – The internal rate of return and present discounted net worth are given for the range of interest rates specified on control card 6.

Stand replacement option. – The output for this option first gives present discounted net worth for the future timber growing opportunity for the range of interest rates specified. Internal rate of return can be read from this. For problem 4, it is between 5.6 and 5.7 percent. For problem 5, it is between 4.8 and 4.9 percent for alternative or plan 1 and between 7.4 and 7.5 percent for alternative or plan 2.

Second, the output gives present discounted net worth for the future timber growing plan and present stand conversion plan combined. In interpreting this information, the user must specify the minimum acceptable return. If a 3.5 percent return is acceptable, in the case of problem 4 the manager would be financially ahead (present discounted net worth is greater) to hold the stand for another 10 years because present worth is greater under this plan. In the case of problem 5, if 3.6 percent return was acceptable it would be financially advantageous to cut the poor stand on the better land.

TSI option. – The output for this option includes the present discounted net worth for the two TSI plans compared under each of the six possible alternatives or plan comparisons. In addition it gives the present discounted net worth due to the difference between the plans compared. In the case of thinning compared with no cultural work, the internal rate of return for the thinning investment is between 5.2 and 5.3 percent. In the case of a program of thinning and pruning, internal rate of return on investment is between 4.5 and 4.6 percent indicating that pruning only lessened the financial opportunity.

Problem 7. It is obvious from this analysis that there is no financial advantage in leaving seed trees (plan 1). The calculations suggest the manager should evaluate closely seed production on the area prior to cutting. For obvious reasons he could not wait to see what the seed crop was likely to be before planning for future timber growing. However, financing for timber growing could be planned on the basis of plan 4 or plan 2.

Figure 14. Computer output, Problem 1.

```
                                        INVESTMENT ANALYSIS PROGRAM NO.6.  INT. STA.

PROBLEM NO.    1--SAMPLE PROBLEM -PERIODIC COSTS AND INCOMES--


        PLAN 1--113 YEAR ROTATION
        PLAN 2--100 YEAR ROTATION

                                                        GENERAL EVALUATION OF ALTERNATIVES

                    RINT  RINT  RINT JPR
CONTROL CARD 6      .020  .001  .040   1

                   LX  LI  LI  LI  LI  LI  LI   LY   LY   LY   LY   LY   LY  KX KCXX KCX KCX
CONTROL CARD 7      2   1   2   0   0   0   0  113  100    0    0    0    0   0    5   5   5

                  JXX  JX  JX  JX  JX  JX  JX NZZ  NZ  NZ  NZ  NZ  NZ  NZ IST  MX
CONTROL CARD 7      0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0

                                                        ROTATION LENGTH IN YEARS
          1                   2
        113                 100

PERIODIC COSTS AND INCOMES
 YEAR      COST       YEAR      COST       YEAR       COST       YEAR       COST       YEAR
    0     -3.00          0    -11.00
    1    -15.00          1    -25.00
   18    -35.00         16    -20.00
   60     97.20         60    145.80
  113    456.00        100    414.00



PROBLEM NO. 1--SAMPLE PROBLEM -PERIODIC COSTS AND INCOMES--

INTERNAL RATE OF RETURN FOR SCHEDULE 0001 IS BETWEEN   2.7 AND   2.8
WITH PRESENT WORTHS OF   2.99 AND  -0.23 RESPECTIVELY.

INTERNAL RATE OF RETURN FOR SCHEDULE 0002 IS BETWEEN   2.9 AND   3.0
WITH PRESENT WORTHS OF   2.14 AND  -1.53 RESPECTIVELY.

  PRESENT DISCOUNTED NET WORTH AT GIVEN ALTERNATIVE RATES OF INTEREST
                ALT-PLAN  1        ALT-PLAN  2        ALT-PLAN  0        ALT-PLAN  0
  RATE      (ROTATION 113)     (ROTATION 100)     (ROTATION   0)     (ROTATION   0)

   2.0              40.38              59.75
   2.1              32.86              50.16
   2.2              26.25              41.63
   2.3              20.41              34.02
   2.4              15.25              27.22
   2.5              10.67              21.11
   2.6               6.61              15.61
   2.7               2.99              10.66
   2.8              -0.23               6.19
   2.9              -3.10               2.14
   3.0              -5.67              -1.53
   3.1              -7.96              -4.85
   3.2             -10.01              -7.87
   3.3             -11.85             -10.62
   3.4             -13.49             -13.12
   3.5             -14.96             -15.40
   3.6             -16.27             -17.48
   3.7             -17.45             -19.38
   3.8             -18.50             -21.11
   3.9             -19.44             -22.69
   4.0             -20.28             -24.14
```

Figure 15. – Computer output, Problem 2.

```
PROBLEM NO.   2--SAMPLE PROBLEM--PERIODIC AND ANNUAL COSTS AND INCOMES                    ID=  2


        PLAN 1--PERPETUATED SERIES
        PLAN 2--TERMINATED SERIES

                                                GENERAL EVALUATION OF ALTERNATIVES

                    RINT  RINT  RINT JPR
CONTROL CARD 6      .005  .001  .100   1

                   LX  LI  LI  LI  LI  LI  LI   LY   LY   LY   LY   LY   LY  KX KCXX KCX KCX KCX KCX KCX KCX
CONTROL CARD 7      2   1   2   0   0   0   0   40   40    0    0    0    0   0    9   9   9   0   0   0   0

                  JXX  JX  JX  JX  JX  JX  JX NZZ  NZ  NZ  NZ  NZ  NZ  NZ IST  MX
CONTROL CARD 7      1   1   1   0   0   0   0   1   0   1   0   0   0   0   0   0

                                                ROTATION LENGTH IN YEARS

          1                   2
         40                  40

PERIODIC COSTS AND INCOMES
 YEAR      COST      YEAR      COST      YEAR      COST      YEAR      COST      YEAR      COST      YEAR      COST
    0    -25.00         0    -25.00
    0    -20.00         0    -20.00
    4     -6.00         4     -6.00
    8     -3.00         8     -3.00
   15     20.00        15     20.00
   25     36.00        25     36.00
   33     40.00        33     40.00
   40    450.00        40    450.00
   40     25.00        40     25.00

ANNUAL COSTS AND RETURNS--ALT. OR PLAN   1
        1ST YEAR   0  END YEAR  40  $    -1.12  CHANGE       0

ANNUAL COSTS AND RETURNS--ALT. OR PLAN   2
        1ST YEAR   0  END YEAR  40  $    -1.12  CHANGE       0
```

PROBLEM NO. 2--SAMPLE PROBLEM--PERIODIC AND ANNUAL COSTS AND INCOMES

INTERNAL RATE OF RETURN FOR SCHEDULE 0001 IS BETWEEN 6.0 AND 6.1
WITH PRESENT WORTHS OF .30 AND -1.86 RESPECTIVELY.

INTERNAL RATE OF RETURN FOR SCHEDULE 0002 IS BETWEEN 6.0 AND 6.1
WITH PRESENT WORTHS OF .27 AND -1.68 RESPECTIVELY.

PRESENT DISCOUNTED NET WORTH AT GIVEN ALTERNATIVE RATES OF INTEREST

RATE	ALT-PLAN 1 (ROTATION 40)	ALT-PLAN 2 (ROTATION 40)	ALT-PLAN 0 (ROTATION 0)
.5	2095.98	379.08	
.6	1703.84	362.59	
.7	1424.13	346.75	
.8	1214.69	331.52	
.9	1052.09	316.89	
1.0	922.28	302.83	
1.1	816.31	289.31	
1.2	728.23	276.32	
1.3	653.91	263.84	
1.4	590.39	251.84	
1.5	535.52	240.31	
1.6	487.67	229.22	
1.7	445.61	218.56	
1.8	408.37	208.32	
1.9	375.18	198.47	
2.0	345.44	188.99	
2.1	318.66	179.89	
2.2	294.42	171.13	
2.3	272.41	162.71	
2.4	252.33	154.61	
2.5	233.96	146.83	
2.6	217.10	139.34	
2.7	201.58	132.14	
2.8	187.26	125.21	
2.9	174.00	118.55	
3.0	161.71	112.14	
3.1	150.29	105.97	
3.2	139.66	100.04	
3.3	129.75	94.34	
3.4	120.48	88.85	
3.5	111.81	83.57	
3.6	103.69	78.49	
3.7	96.06	73.60	
3.8	88.90	68.90	
3.9	82.16	64.38	
4.0	75.81	60.02	
4.1	69.83	55.83	
4.2	64.18	51.80	
4.3	58.84	47.92	
4.4	53.79	44.18	
4.5	49.01	40.59	
4.6	44.49	37.13	
4.7	40.20	33.80	
4.8	36.13	30.59	
4.9	32.26	27.50	
5.0	28.59	24.53	
5.1	25.11	21.67	
5.2	21.79	18.92	
5.3	18.63	16.27	
5.4	15.62	13.72	
5.5	12.76	11.26	
5.6	10.03	8.89	
5.7	7.42	6.61	
5.8	4.94	4.42	
5.9	2.57	2.31	
6.0	.30	.27	
6.1	-1.86	-1.68	
6.2	-3.92	-3.57	
6.3	-5.90	-5.39	
6.4	-7.79	-7.14	
6.5	-9.60	-8.82	
6.6	-11.32	-10.45	
6.7	-12.98	-12.01	
6.8	-14.56	-13.52	
6.9	-16.08	-14.97	
7.0	-17.53	-16.36	
7.1	-18.93	-17.71	
7.2	-20.26	-19.01	
7.3	-21.54	-20.25	
7.4	-22.77	-21.46	
7.5	-23.94	-22.62	
7.6	-25.07	-23.73	
7.7	-26.15	-24.81	
7.8	-27.19	-25.84	
7.9	-28.19	-26.84	
8.0	-29.15	-27.80	
8.1	-30.07	-28.73	
8.2	-30.95	-29.62	
8.3	-31.79	-30.48	
8.4	-32.61	-31.31	
8.5	-33.39	-32.11	
8.6	-34.14	-32.88	
8.7	-34.86	-33.62	
8.8	-35.56	-34.34	
8.9	-36.22	-35.02	
9.0	-36.86	-35.69	
9.1	-37.48	-36.33	
9.2	-38.07	-36.94	
9.3	-38.64	-37.54	
9.4	-39.18	-38.11	
9.5	-39.71	-38.66	
9.6	-40.22	-39.19	
9.7	-40.70	-39.70	
9.8	-41.17	-40.19	
9.9	-41.62	-40.67	
10.0	-42.05	-41.12	

Figure 16. — Computer output, Problem 3.

```
PROBLEM NO.    3--SAMPLE PROBLEM--PERIODIC COSTS AND INCOMES AND YIELD CALCULATIONS            ID=  1


    SAME AS PROBLEM 1 BUT WITH PRODUCT YIELDS COMPUTED BY THE MACHINE

                                                GENERAL EVALUATION OF ALTERNATIVES

                    RINT  RINT  RINT JPR
CONTROL CARD 6      .020  .001  .040   1

                   LX  LI  LI  LI  LI  LI  LI   LY   LY   LY   LY   LY   LY  KX KCXX KCX KCX KCX KCX KCX KCX
CONTROL CARD 7      2   1   2   0   0   0   0  113  100    0    0    0    0   1    3   3   3   0   0   0   0

                  JXX  JX  JX  JX  JX  JX  JX NZZ  NZ  NZ  NZ  NZ  NZ  NZ IST  MX
CONTROL CARD 7      0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1

                                                ROTATION LENGTH IN YEARS

         1                   2
       113                 100

PERIODIC COSTS AND INCOMES
 YEAR      COST       YEAR      COST       YEAR      COST       YEAR      COST       YEAR      COST       YEAR      COST
    0     -3.00          0    -11.00
    1    -15.00          1    -25.00
   18    -35.00         16    -20.00

                   K1XX  K1X  K1X  K1X  K1X  K1X  K1X
CONTROL CARD 11       6    6    4    0    0    0    0
                   K2XX  K2X  K2X  K2X  K2X  K2X  K2X
CONTROL CARD 11       0    0    0    0    0    0    0
                   K3XX  K3X  K3X  K3X  K3X  K3X  K3X
CONTROL CARD 11       0    0    0    0    0    0    0

PERIODIC RETURNS FROM SAWTIMBER--CU FT
  YEAR YIELD QUAL      YEAR YIELD QUAL      YEAR YIELD QUAL      YEAR YIELD QUAL      YEAR YIELD QUAL      YEAR YIELD QUAL
    60  9720   60        60 12150   50
    60  3240   50        60 12150   70
    60  3240   70       100 38000   50
   113 51600   60       100 32000   70
   113 12200   50         0     0    0
   113 12200   70         0     0    0

 PRODUCT PRICES
             PRODUCT NO.1              PRODUCT NO.2              PRODUCT NO.3

        $      .100  CH       0
```

PROBLEM NO. 3--SAMPLE PROBLEM--PERIODIC COSTS AND INCOMES AND YIELD CALCULATIONS

INTERNAL RATE OF RETURN FOR SCHEDULE 0001 IS BETWEEN 2.7 AND 2.8
WITH PRESENT WORTHS OF 2.99 AND -0.23 RESPECTIVELY.

INTERNAL RATE OF RETURN FOR SCHEDULE 0002 IS BETWEEN 2.9 AND 3.0
WITH PRESENT WORTHS OF 2.14 AND -1.53 RESPECTIVELY.

PRESENT DISCOUNTED NET WORTH AT GIVEN ALTERNATIVE RATES OF INTEREST

RATE	ALT-PLAN 1 (ROTATION 113)	ALT-PLAN 2 (ROTATION 100)	ALT-PLAN 0 (ROTATION 0)	ALT-PLAN 0 (ROTATION 0)	ALT-PLAN 0 (ROTATION 0)	ALT-PLAN 0 (ROTATION 0)
2.0	40.38	59.75				
2.1	32.86	50.16				
2.2	26.25	41.63				
2.3	20.41	34.02				
2.4	15.25	27.22				
2.5	10.67	21.11				
2.6	6.61	15.61				
2.7	2.99	10.66				
2.8	-0.23	6.19				
2.9	-3.10	2.14				
3.0	-5.67	-1.53				
3.1	-7.96	-4.85				
3.2	-10.01	-7.87				
3.3	-11.85	-10.62				
3.4	-13.49	-13.12				
3.5	-14.96	-15.40				
3.6	-16.27	-17.48				
3.7	-17.45	-19.38				
3.8	-18.50	-21.11				
3.9	-19.44	-22.69				
4.0	-20.28	-24.14				

Figure 17. – Computer output, Problem 4.

```
PROBLEM NO.    4--SAMPLE PROBLEM--STAND REPLACEMENT--CUT NOW OR IN 10 YEARS                    ID=  3


        PLAN 1--CUT NOW
        PLAN 2--CUT IN 10 YEARS
             SAME FUTURE TIMBER GROWING PROGRAM IN BOTH PLANS

                                          EVALUATION OF STAND REPLACEMENT PRIORITIES

                  RINT  RINT  RINT JPR
CONTROL CARD 6     .010  .001  .070   2

CONTROL CARDS FOR FUTURE STANDS*****

                  LX  LI  LI  LI  LI  LI  LI   LY   LY   LY   LY   LY   LY  KX KCXX KCX KCX KCX KCX KCX KCX
CONTROL CARD 7     2   1   2   0   0   0   0   81   81    0    0    0    0   1    2   2   2   0   0   0   0

                 JXX  JX  JX  JX  JX  JX  JX NZZ  NZ  NZ  NZ  NZ  NZ  NZ IST  MX
CONTROL CARD 7     0   0   0   0   0   0   0   0   0   0   0   0   0   0   1   1

                                                    ROTATION LENGTH IN YEARS

          1                    2
         81                   81

PERIODIC COSTS AND INCOMES
 YEAR      COST       YEAR      COST       YEAR      COST       YEAR      COST       YEAR      COST       YEAR      COST
    1     -5.00          1     -5.00
   21    -22.00         21    -22.00

                 K1XX  K1X  K1X  K1X  K1X  K1X  K1X
CONTROL CARD 11     2    2    2    0    0    0    0
                 K2XX  K2X  K2X  K2X  K2X  K2X  K2X
CONTROL CARD 11     0    0    0    0    0    0    0
                 K3XX  K3X  K3X  K3X  K3X  K3X  K3X
CONTROL CARD 11     0    0    0    0    0    0    0

PERIODIC RETURNS FROM SAWTIMBER--100 CU FT
  YEAR YIELD QUAL      YEAR YIELD QUAL      YEAR YIELD QUAL      YEAR YIELD QUAL      YEAR YIELD QUAL      YEAR YIELD QUAL
    51   250   35        51   250   35
    81   900  110        81   900  110

 PRODUCT PRICES
             PRODUCT NO.1              PRODUCT NO.2              PRODUCT NO.3

         $    5.000  CH   .005
```

PROBLEM NO. 4--SAMPLE PROBLEM--STAND REPLACEMENT--CUT NOW OR IN 10 YEARS

DISCOUNTED NET WORTH OF FUTURE CROPS

RATE	ALT-PLAN 1 (ROTATION 81)	ALT-PLAN 2 (ROTATION 81)	ALT-PLAN 0 (ROTATION 0)
1.0	579.90	579.90	
1.1	503.11	503.11	
1.2	439.82	439.82	
1.3	386.91	386.91	
1.4	342.14	342.14	
1.5	303.88	303.88	
1.6	270.90	270.90	
1.7	242.26	242.26	
1.8	217.23	217.23	
1.9	195.22	195.22	
2.0	175.78	175.78	
2.1	158.53	158.53	
2.2	143.17	143.17	
2.3	129.45	129.45	
2.4	117.14	117.14	
2.5	106.08	106.08	
2.6	96.11	96.11	
2.7	87.10	87.10	
2.8	78.95	78.95	
2.9	71.56	71.56	
3.0	64.85	64.85	
3.1	58.75	58.75	
3.2	53.19	53.19	
3.3	48.12	48.12	
3.4	43.50	43.50	
3.5	39.27	39.27	
3.6	35.41	35.41	
3.7	31.87	31.87	
3.8	28.63	28.63	
3.9	25.66	25.66	
4.0	22.94	22.94	
4.1	20.44	20.44	
4.2	18.14	18.14	
4.3	16.04	16.04	
4.4	14.10	14.10	
4.5	12.32	12.32	
4.6	10.69	10.69	
4.7	9.19	9.19	
4.8	7.81	7.81	
4.9	6.54	6.54	
5.0	5.37	5.37	
5.1	4.30	4.30	
5.2	3.31	3.31	
5.3	2.40	2.40	
5.4	1.57	1.57	
5.5	.80	.80	
5.6	.09	.09	
5.7	-0.55	-0.55	
5.8	-1.15	-1.15	
5.9	-1.69	-1.69	
6.0	-2.19	-2.19	
6.1	-2.65	-2.65	
6.2	-3.07	-3.07	
6.3	-3.46	-3.46	
6.4	-3.81	-3.81	
6.5	-4.13	-4.13	
6.6	-4.43	-4.43	
6.7	-4.70	-4.70	
6.8	-4.94	-4.94	
6.9	-5.17	-5.17	
7.0	-5.37	-5.37	

CONTROL CARDS 7* FOR PRESENT STAND*****

	LX	LI	LI	LI	LI	LI	LI	LY	LY	LY	LY	LY	LY	KX	KCXX	KCX	KCX	KCX	KCX	KCX	KCX
CONTROL CARD 7	2	1	2	0	0	0	0	0	10	0	0	0	0	1	0	0	0	0	0	0	0

	JXX	JX	JX	JX	JX	JX	JX	NZZ	NZ	NZ	NZ	NZ	NZ	NZ	IST	MX
CONTROL CARD 7	0	0	0	0	0	0	0	1	1	1	0	0	0	0	2	1

ROTATION LENGTH IN YEARS

	1								2												
	0								10												

	K1XX	K1X	K1X	K1X	K1X	K1X	K1X
CONTROL CARD 11	1	1	1	0	0	0	0
	K2XX	K2X	K2X	K2X	K2X	K2X	K2X
CONTROL CARD 11	0	0	0	0	0	0	0
	K3XX	K3X	K3X	K3X	K3X	K3X	K3X
CONTROL CARD 11	0	0	0	0	0	0	0

PERIODIC RETURNS FROM SAWTIMBER--100 CU FT

YEAR	YIELD	QUAL	YEAR	YIELD	QUAL	YEAR	YIELD	QUAL	YEAR	YIELD	QUAL	YEAR	YIELD	QUAL	YEAR	YIELD	QUAL
0	700	90	10	800	110												

PRODUCT PRICES

	PRODUCT NO.1		PRODUCT NO.2		PRODUCT NO.3	
$	5.000	CH	.005			

PROBLEM NO. 4--SAMPLE PROBLEM--STAND REPLACEMENT--CUT NOW OR IN 10 YEARS

DISCOUNTED NET WORTH OF PRESENT AND FUTURE CROPS

RATE	ALT-PLAN 1 (ROTATION 0)	ALT-PLAN 2 (ROTATION 10)
1.0	894.90	943.22
1.1	818.11	865.10
1.2	754.82	800.41
1.3	701.91	746.05
1.4	657.14	699.77
1.5	618.88	659.94
1.6	585.90	625 33
1.7	557.26	595.01
1.8	532.23	568.25
1.9	510.22	544.46
2.0	490.78	523.20
2.1	473.53	504.09
2.2	458.17	486.82
2.3	444.45	471.15
2.4	432.14	456.86
2.5	421.08	443.78
2.6	411.11	431.76
2.7	402.10	420.68
2.8	393.95	410.42
2.9	386.56	400.90
3.0	379.85	392.03
3.1	373.75	383.74
3.2	368.19	375.99
3.3	363.12	368.70
3.4	358.50	361.84
3.5	354.27	355.36
3.6	350.41	349.23
3.7	346.87	343.42
3.8	343.63	337.89
3.9	340.66	332.63
4.0	337.94	327.61
4.1	335.44	322.80
4.2	333.14	318.20
4.3	331.04	313.78
4.4	329.10	309.52
4.5	327.32	305.43
4.6	325.69	301.48
4.7	324.19	297.66
4.8	322.81	293.97
4.9	321.54	290.39
5.0	320.37	286.92
5.1	319.30	283.55
5.2	318.31	280.27
5.3	317.40	277.08
5.4	316.57	273.97
5.5	315.80	270.94
5.6	315.09	267.97
5.7	314.45	265.08
5.8	313.85	262.24
5.9	313.31	259.47
6.0	312.81	256.75
6.1	312.35	254.09
6.2	311.93	251.48
6.3	311.54	248.91
6.4	311.19	246.39
6.5	310.87	243.92
6.6	310.57	241.48
6.7	310.30	239.09
6.8	310.06	236.73
6.9	309.83	234.41
7.0	309.63	232.13

Figure 18. – Computer output, Problem 5.

```
PROBLEM NO.    5--SAMPLE PROBLEM--STAND REPLACEMENT -COMPARISON OF 2 STANDS                    ID=  2


        PLAN 1--CUT HIGHEST VOLUME STAND ON POOR LAND
        PLAN 2--CUT LOW VOLUME STAND ON GOOD LAND

                                          EVALUATION OF STAND REPLACEMENT PRIORITIES

                  RINT  RINT  RINT JPR
CONTROL CARD 6    .010  .001  .100   2

CONTROL CARDS FOR FUTURE STANDS*****

                  LX  LI  LI  LI  LI  LI  LI   LY   LY   LY   LY   LY   LY  KX KCXX KCX KCX KCX KCX KCX KCX
CONTROL CARD 7     2   3   7   0   0   0   0  110   81    0    0    0    0   1    1   1   1   0   0   0   0

                 JXX  JX  JX  JX  JX  JX  JX NZZ  NZ  NZ  NZ  NZ  NZ  NZ IST  MX
CONTROL CARD 7     0   0   0   0   0   0   0   0   0   0   0   0   0   0   1   1

                                                        ROTATION LENGTH IN YEARS
          3                    7
        110                   81

PERIODIC COSTS AND INCOMES
 YEAR      COST       YEAR      COST       YEAR      COST       YEAR      COST       YEAR      COST       YEAR      COST
   30    -25.00         15    -25.00

                 K1XX  K1X  K1X  K1X  K1X  K1X  K1X
CONTROL CARD 11     2    2    2    0    0    0    0
                 K2XX  K2X  K2X  K2X  K2X  K2X  K2X
CONTROL CARD 11     0    0    0    0    0    0    0
                 K3XX  K3X  K3X  K3X  K3X  K3X  K3X
CONTROL CARD 11     0    0    0    0    0    0    0

PERIODIC RETURNS FROM SAWTIMBER--100 CU FT
  YEAR YIELD QUAL      YEAR YIELD QUAL      YEAR YIELD QUAL      YEAR YIELD QUAL      YEAR YIELD QUAL      YEAR YIELD QUAL
    75   200   35        50   300   50
   110   800   90        81  1200  140

 PRODUCT PRICES
             PRODUCT NO.1              PRODUCT NO.2              PRODUCT NO.3

        $    7.000  CH   .005
```

PROBLEM NO. 5--SAMPLE PROBLEM--STAND REPLACEMENT -COMPARISON OF 2 STANDS

DISCOUNTED NET WORTH OF FUTURE CROPS

RATE	ALT-PLAN 3 (ROTATION 110)	ALT-PLAN 7 (ROTATION 81)
1.0	413.13	1438.99
1.1	351.73	1252.02
1.2	301.59	1097.88
1.3	260.11	968.96
1.4	225.39	859.84
1.5	196.06	766.54
1.6	171.09	686.07
1.7	149.70	616.15
1.8	131.26	555.00
1.9	115.29	501.21
2.0	101.40	453.67
2.1	89.27	411.45
2.2	78.65	373.82
2.3	69.33	340.16
2.4	61.12	309.96
2.5	53.88	282.78
2.6	47.48	258.26
2.7	41.81	236.09
2.8	36.79	216.00
2.9	32.34	197.76
3.0	28.39	181.18
3.1	24.87	166.07
3.2	21.74	152.29
3.3	18.96	139.71
3.4	16.48	128.20
3.5	14.28	117.67
3.6	12.31	108.02
3.7	10.56	99.17
3.8	9.01	91.04
3.9	7.62	83.58
4.0	6.38	76.71
4.1	5.28	70.40
4.2	4.31	64.59
4.3	3.44	59.24
4.4	2.67	54.30
4.5	1.99	49.76
4.6	1.38	45.56
4.7	.85	41.69
4.8	.38	38.12
4.9	-0.04	34.83
5.0	-0.40	31.78
5.1	-0.72	28.97
5.2	-1.00	26.37
5.3	-1.25	23.97
5.4	-1.46	21.75
5.5	-1.64	19.69
5.6	-1.80	17.80
5.7	-1.93	16.04
5.8	-2.05	14.42
5.9	-2.14	12.92
6.0	-2.22	11.53
6.1	-2.28	10.25
6.2	-2.33	9.06
6.3	-2.37	7.96
6.4	-2.40	6.95
6.5	-2.42	6.01
6.6	-2.43	5.14
6.7	-2.43	4.34
6.8	-2.43	3.60
6.9	-2.42	2.92
7.0	-2.41	2.29
7.1	-2.39	1.71
7.2	-2.37	1.17
7.3	-2.34	.68
7.4	-2.32	.22
7.5	-2.29	-0.20
7.6	-2.25	-0.59
7.7	-2.22	-0.94
7.8	-2.18	-1.27
7.9	-2.15	-1.57
8.0	-2.11	-1.84
8.1	-2.07	-2.10
8.2	-2.03	-2.33
8.3	-1.99	-2.54
8.4	-1.96	-2.73
8.5	-1.92	-2.91
8.6	-1.88	-3.07
8.7	-1.84	-3.21
8.8	-1.80	-3.34
8.9	-1.76	-3.46
9.0	-1.72	-3.57
9.1	-1.68	-3.66
9.2	-1.64	-3.75
9.3	-1.61	-3.82
9.4	-1.57	-3.89
9.5	-1.53	-3.95
9.6	-1.50	-4.00
9.7	-1.46	-4.04
9.8	-1.43	-4.08
9.9	-1.39	-4.11
10.0	-1.36	-4.14

CONTROL CARDS 7+ FOR PRESENT STAND*****

	LX	LI	LI	LI	LI	LI	LI	LY	LY	LY	LY	LY	LY	KX	KCXX	KCX	KCX	KCX	KCX	KCX	KCX
CONTROL CARD 7	2	3	7	0	0	0	0	3	3	0	0	0	0	1	2	2	2	0	0	0	0

	JXX	JX	JX	JX	JX	JX	JX	NZZ	NZ	NZ	NZ	NZ	NZ	NZ	IST	MX
CONTROL CARD 7	0	0	0	0	0	0	0	1	1	1	0	0	0	0	2	1

ROTATION LENGTH IN YEARS

	3		7
	3		3

PERIODIC COSTS AND INCOMES

YEAR	COST	YEAR	COST	YEAR	COST	YEAR	COST	YEAR	COST	YEAR	COST
1	-7.00	1	-6.00								
2	-24.00	2	-22.00								

	K1XX	K1X	K1X	K1X	K1X	K1X	K1X
CONTROL CARD 11	1	1	1	0	0	0	0

	K2XX	K2X	K2X	K2X	K2X	K2X	K2X
CONTROL CARD 11	0	0	0	0	0	0	0

	K3XX	K3X	K3X	K3X	K3X	K3X	K3X
CONTROL CARD 11	0	0	0	0	0	0	0

PERIODIC RETURNS FROM SAWTIMBER--100 CU FT

YEAR	YIELD	QUAL	YEAR	YIELD	QUAL	YEAR	YIELD	QUAL	YEAR	YIELD	QUAL	YEAR	YIELD	QUAL	YEAR	YIELD	QUAL
3	740	90	3	590	90												

PRODUCT PRICES

	PRODUCT NO.1		PRODUCT NO.2		PRODUCT NO.3	
$	7.000	CH	.005			

PROBLEM NO. 5--SAMPLE PROBLEM--STAND REPLACEMENT -COMPARISON OF 2 STANDS

DISCOUNTED NET WORTH OF PRESENT AND FUTURE CROPS

RATE	ALT-PLAN 3 (ROTATION 3)	ALT-PLAN 7 (ROTATION 3)
1.0	829.80	1735.34
1.1	767.88	1549.23
1.2	717.20	1395.89
1.3	675.13	1267.71
1.4	639.80	1159.26
1.5	609.82	1066.59
1.6	584.19	986.68
1.7	562.09	917.27
1.8	542.92	856.57
1.9	526.19	803.18
2.0	511.52	755.99
2.1	498.59	714.07
2.2	487.14	676.70
2.3	476.97	643.24
2.4	467.89	613.20
2.5	459.76	586.13
2.6	452.46	561.69
2.7	445.88	539.55
2.8	439.92	519.45
2.9	434.52	501.17
3.0	429.60	484.50
3.1	425.11	469.28
3.2	420.99	455.35
3.3	417.21	442.58
3.4	413.73	430.86
3.5	410.50	420.08
3.6	407.51	410.15
3.7	404.73	401.00
3.8	402.14	392.54
3.9	399.71	384.73
4.0	397.42	377.48
4.1	395.27	370.77
4.2	393.24	364.54
4.3	391.31	358.74
4.4	389.47	353.35
4.5	387.72	348.32
4.6	386.05	343.63
4.7	384.45	339.24
4.8	382.90	335.14
4.9	381.42	331.30
5.0	379.98	327.69
5.1	378.58	324.30
5.2	377.23	321.12
5.3	375.92	318.12
5.4	374.63	315.28
5.5	373.38	312.61
5.6	372.15	310.08
5.7	370.95	307.69
5.8	369.77	305.42
5.9	368.62	303.26
6.0	367.48	301.21
6.1	366.35	299.25
6.2	365.24	297.39
6.3	364.15	295.61
6.4	363.07	293.91
6.5	362.00	292.27
6.6	360.94	290.71
6.7	359.89	289.20
6.8	358.85	287.76
6.9	357.82	286.36
7.0	356.80	285.02
7.1	355.78	283.72
7.2	354.77	282.46
7.3	353.77	281.24
7.4	352.77	280.06
7.5	351.78	278.91
7.6	350.80	277.80
7.7	349.82	276.71
7.8	348.84	275.65
7.9	347.87	274.62
8.0	346.90	273.61
8.1	345.94	272.63
8.2	344.98	271.66
8.3	344.03	270.72
8.4	343.08	269.79
8.5	342.13	268.88
8.6	341.18	267.98
8.7	340.24	267.11
8.8	339.31	266.24
8.9	338.37	265.39
9.0	337.44	264.55
9.1	336.51	263.72
9.2	335.59	262.91
9.3	334.67	262.10
9.4	333.75	261.31
9.5	332.83	260.52
9.6	331.92	259.74
9.7	331.01	258.97
9.8	330.10	258.21
9.9	329.20	257.46
10.0	328.30	256.71

Figure 19. – Computer output, Problem 6.

```
PROBLEM NO.   6--SAMPLE PROBLEM--TSI OPTION WITH 2 COMPARISONS                    ID=  2


        PLAN 1--COMPARE THINNING WITH NO TREATMENT
        PLAN 2--COMPARE THINNING AND PRUNING WITH NO TREATMENT

                                    EVALUATION OF TIMBER STAND IMPROVEMENT PROGRAMS

                  RINT  RINT  RINT JPR
CONTROL CARD 6    .010  .001  .150   3

CONTROL CARDS FOR FIRST TSI PLAN*****

                 LX  LI  LI  LI  LI  LI  LI   LY   LY   LY   LY   LY   LY  KX KCXX KCX KCX KCX KCX KCX KCX
CONTROL CARD 7    2   1   2   0   0   0   0  100  100    0    0    0    0   1    0   0   0   0   0   0   0

                JXX  JX  JX  JX  JX  JX  JX NZZ  NZ  NZ  NZ  NZ  NZ  NZ IST  MX
CONTROL CARD 7    0   0   0   0   0   0   0   1   1   1   0   0   0   0   1   1

                                                    ROTATION LENGTH IN YEARS

        1                   2
      100                 100

                 K1XX  K1X  K1X  K1X  K1X  K1X  K1X
CONTROL CARD 11     1    1    1    0    0    0    0
                 K2XX  K2X  K2X  K2X  K2X  K2X  K2X
CONTROL CARD 11     0    0    0    0    0    0    0
                 K3XX  K3X  K3X  K3X  K3X  K3X  K3X
CONTROL CARD 11     0    0    0    0    0    0    0

PERIODIC RETURNS FROM SAWTIMBER--MBF
  YEAR YIELD QUAL      YEAR YIELD QUAL      YEAR YIELD QUAL      YEAR YIELD QUAL      YEAR YIELD QUAL      YEAR YIELD QUAL
   100   300   90       100   300   90

 PRODUCT PRICES
             PRODUCT NO.1              PRODUCT NO.2              PRODUCT NO.3

        $   10.000  CH   .005
```

PROBLEM NO. 6--SAMPLE PROBLEM--TSI OPTION WITH 2 COMPARISONS

DISCOUNTED NET WORTH--FIRST TSI PLAN

RATE	ALT-PLAN 1 (ROTATION 100)	ALT-PLAN 2 (ROTATION 100)
1.0	149.73	149.73
1.1	135.62	135.62
1.2	122.86	122.86
1.3	111.30	111.30
1.4	100.85	100.85
1.5	91.38	91.38
1.6	82.81	82.81
1.7	75.05	75.05
1.8	68.03	68.03
1.9	61.66	61.66
2.0	55.90	55.90
2.1	50.69	50.69
2.2	45.96	45.96
2.3	41.68	41.68
2.4	37.80	37.80
2.5	34.28	34.28
2.6	31.10	31.10
2.7	28.21	28.21
2.8	25.59	25.59
2.9	23.22	23.22
3.0	21.07	21.07
3.1	19.12	19.12
3.2	17.36	17.36
3.3	15.76	15.76
3.4	14.30	14.30
3.5	12.98	12.98
3.6	11.79	11.79
3.7	10.70	10.70
3.8	9.72	9.72
3.9	8.83	8.83
4.0	8.02	8.02
4.1	7.28	7.28
4.2	6.62	6.62
4.3	6.01	6.01
4.4	5.46	5.46
4.5	4.96	4.96
4.6	4.51	4.51
4.7	4.10	4.10
4.8	3.73	3.73
4.9	3.39	3.39
5.0	3.08	3.08
5.1	2.80	2.80
5.2	2.55	2.55
5.3	2.32	2.32
5.4	2.11	2.11
5.5	1.92	1.92
5.6	1.74	1.74
5.7	1.58	1.58
5.8	1.44	1.44
5.9	1.31	1.31
6.0	1.19	1.19
6.1	1.09	1.09
6.2	.99	.99
6.3	.90	.90
6.4	.82	.82
6.5	.75	.75
6.6	.68	.68
6.7	.62	.62
6.8	.56	.56
6.9	.51	.51
7.0	.47	.47
7.1	.43	.43
7.2	.39	.39
7.3	.35	.35
7.4	.32	.32
7.5	.29	.29
7.6	.27	.27
7.7	.24	.24
7.8	.22	.22
7.9	.20	.20
8.0	.18	.18
8.1	.17	.17
8.2	.15	.15
8.3	.14	.14
8.4	.13	.13
8.5	.12	.12
8.6	.11	.11
8.7	.10	.10
8.8	.09	.09
8.9	.08	.08
9.0	.07	.07
9.1	.07	.07
9.2	.06	.06
9.3	.06	.06
9.4	.05	.05
9.5	.05	.05
9.6	.04	.04
9.7	.04	.04
9.8	.04	.04
9.9	.03	.03
10.0	.03	.03

CONTROL CARDS 7+ FOR SECOND TSI PLAN*****

	LX	LI	LI	LI	LI	LI	LI	LY	LY	LY	LY	LY	LY	KX	KCXX	KCX	KCX	KCX	KCX	KCX	KCX
CONTROL CARD 7	2	1	2	0	0	0	0	80	80	0	0	0	0	1	2	1	2	0	0	0	0

	JXX	JX	JX	JX	JX	JX	JX	NZZ	NZ	NZ	NZ	NZ	NZ	NZ	IST	MX
CONTROL CARD 7	0	0	0	0	0	0	0	1	1	1	0	0	0	0	2	1

ROTATION LENGTH IN YEARS

1	2
80	80

PERIODIC COSTS AND INCOMES

YEAR	COST	YEAR	COST	YEAR	COST	YEAR	COST	YEAR	COST	YEAR	COST
0	-26.00	0	-26.00								
0	0	0	-30.00								

	K1XX	K1X	K1X	K1X	K1X	K1X	K1X
CONTROL CARD 11	3	3	3	0	0	0	0
	K2XX	K2X	K2X	K2X	K2X	K2X	K2X
CONTROL CARD 11	0	0	0	0	0	0	0
	K3XX	K3X	K3X	K3X	K3X	K3X	K3X
CONTROL CARD 11	0	0	0	0	0	0	0

PERIODIC RETURNS FROM SAWTIMBER--MBF

YEAR	YIELD	QUAL	YEAR	YIELD	QUAL	YEAR	YIELD	QUAL	YEAR	YIELD	QUAL	YEAR	YIELD	QUAL	YEAR	YIELD	QUAL
35	50	50	35	50	35												
55	100	80	55	100	85												
80	700	110	80	700	175												

PRODUCT PRICES

PRODUCT NO.1	PRODUCT NO.2	PRODUCT NO.3
$ 10.000 CH .005		

PROBLEM NO. 6--SAMPLE PROBLEM--TSI OPTION WITH 2 COMPARISONS

DISCOUNTED NET WORTH--SECOND TSI PLAN

RATE	ALT-PLAN 1 (ROTATION 80)	ALT-PLAN 2 (ROTATION 80)
1.0	540.05	794.88
1.1	499.20	732.18
1.2	461.40	674.20
1.3	426.41	620.60
1.4	394.01	571.02
1.5	364.01	525.17
1.6	336.23	482.75
1.7	310.50	443.51
1.8	286.67	407.21
1.9	264.58	373.61
2.0	244.12	342.51
2.1	225.15	313.73
2.2	207.57	287.09
2.3	191.27	262.41
2.4	176.15	239.57
2.5	162.13	218.41
2.6	149.12	198.81
2.7	137.06	180.66
2.8	125.86	163.84
2.9	115.47	148.25
3.0	105.82	133.80
3.1	96.86	120.41
3.2	88.54	108.00
3.3	80.81	96.49
3.4	73.63	85.81
3.5	66.96	75.91
3.6	60.76	66.73
3.7	54.99	58.21
3.8	49.63	50.30
3.9	44.65	42.96
4.0	40.01	36.15
4.1	35.69	29.83
4.2	31.68	23.95
4.3	27.94	18.50
4.4	24.46	13.43
4.5	21.22	8.73
4.6	18.20	4.36
4.7	15.39	.29
4.8	12.77	-3.49
4.9	10.32	-7.00
5.0	8.05	-10.26
5.1	5.92	-13.30
5.2	3.94	-16.13
5.3	2.09	-18.76
5.4	.36	-21.20
5.5	-1.25	-23.48
5.6	-2.76	-25.60
5.7	-4.16	-27.57
5.8	-5.47	-29.41
5.9	-6.70	-31.12
6.0	-7.85	-32.72
6.1	-8.92	-34.20
6.2	-9.93	-35.59
6.3	-10.87	-36.88
6.4	-11.75	-38.09
6.5	-12.57	-39.21
6.6	-13.34	-40.26
6.7	-14.07	-41.24
6.8	-14.74	-42.15
6.9	-15.38	-43.01
7.0	-15.97	-43.80
7.1	-16.53	-44.55
7.2	-17.05	-45.24
7.3	-17.55	-45.89
7.4	-18.01	-46.50
7.5	-18.44	-47.07
7.6	-18.85	-47.60
7.7	-19.23	-48.09
7.8	-19.59	-48.56
7.9	-19.93	-49.00
8.0	-20.25	-49.40
8.1	-20.55	-49.78
8.2	-20.83	-50.14
8.3	-21.10	-50.48
8.4	-21.35	-50.79
8.5	-21.58	-51.09
8.6	-21.81	-51.36
8.7	-22.02	-51.62
8.8	-22.21	-51.86
8.9	-22.40	-52.09
9.0	-22.58	-52.31
9.1	-22.74	-52.51
9.2	-22.90	-52.70
9.3	-23.05	-52.88
9.4	-23.19	-53.04
9.5	-23.32	-53.20
9.6	-23.45	-53.35
9.7	-23.57	-53.49
9.8	-23.68	-53.62
9.9	-23.79	-53.74
10.0	-23.89	-53.86

PROBLEM NO. 6--SAMPLE PROBLEM--TSI OPTION WITH 2 COMPARISONS

DISCOUNTED NET WORTH OF ADDED TSI INVESTMENT

RATE	ALT-PLAN 1 (ROTATION 80)	ALT-PLAN 2 (ROTATION 80)
1.0	390.32	645.15
1.1	363.58	596.55
1.2	338.54	551.34
1.3	315.10	509.29
1.4	293.16	470.17
1.5	272.63	433.79
1.6	253.42	399.94
1.7	235.45	368.46
1.8	218.64	339.18
1.9	202.92	311.94
2.0	188.22	286.61
2.1	174.47	263.05
2.2	161.61	241.13
2.3	149.59	220.74
2.4	138.35	201.77
2.5	127.85	184.13
2.6	118.03	167.72
2.7	108.85	152.45
2.8	100.26	138.24
2.9	92.24	125.03
3.0	84.74	112.73
3.1	77.73	101.29
3.2	71.18	90.64
3.3	65.05	80.73
3.4	59.33	71.51
3.5	53.97	62.93
3.6	48.97	54.94
3.7	44.29	47.50
3.8	39.91	40.58
3.9	35.82	34.13
4.0	31.99	28.13
4.1	28.41	22.54
4.2	25.06	17.34
4.3	21.93	12.49
4.4	19.00	7.97
4.5	16.26	3.76
4.6	13.69	-0.16
4.7	11.29	-3.81
4.8	9.04	-7.21
4.9	6.94	-10.39
5.0	4.97	-13.34
5.1	3.12	-16.10
5.2	1.39	-18.67
5.3	-0.23	-21.07
5.4	-1.74	-23.31
5.5	-3.16	-25.39
5.6	-4.50	-27.34
5.7	-5.75	-29.16
5.8	-6.92	-30.85
5.9	-8.01	-32.43
6.0	-9.04	-33.91
6.1	-10.01	-35.29
6.2	-10.92	-36.58
6.3	-11.77	-37.78
6.4	-12.57	-38.91
6.5	-13.32	-39.96
6.6	-14.02	-40.94
6.7	-14.68	-41.86
6.8	-15.31	-42.72
6.9	-15.89	-43.52
7.0	-16.44	-44.27
7.1	-16.96	-44.97
7.2	-17.44	-45.63
7.3	-17.90	-46.24
7.4	-18.33	-46.82
7.5	-18.73	-47.36
7.6	-19.12	-47.86
7.7	-19.48	-48.34
7.8	-19.81	-48.78
7.9	-20.13	-49.20
8.0	-20.43	-49.59
8.1	-20.72	-49.95
8.2	-20.98	-50.30
8.3	-21.24	-50.62
8.4	-21.47	-50.92
8.5	-21.70	-51.20
8.6	-21.91	-51.47
8.7	-22.11	-51.72
8.8	-22.30	-51.95
8.9	-22.48	-52.17
9.0	-22.65	-52.38
9.1	-22.81	-52.58
9.2	-22.96	-52.76
9.3	-23.11	-52.93
9.4	-23.24	-53.09
9.5	-23.37	-53.25
9.6	-23.49	-53.39
9.7	-23.61	-53.53
9.8	-23.72	-53.65
9.9	-23.82	-53.77
10.0	-23.92	-53.89

Figure 20. — Computer output, Problem 7.

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PROBLEM NO.    7A--COMPARISON OF TIMBER GROWING ALTERNATIVES--55 YEAR ROTATION                ID=  4


        PLAN 1--SEED TREE CUT LEAVING GROUPS OF SEED TREES 1/4 ACRE--10 MBF
        PLAN 2--CLEAR CUT AND PLANT ABOUT HALF THE AREA--NATURAL REGEN ON HALF
        PLAN 3--CLEAR CUT  ASSUMING ALL THE AREAS CUT WILL REGENERATE NATURALLY
        PLAN 4--CLEAR CUT AND SEED HALF THE AREA--NATURAL REGEN ON HALF

                                              GENERAL EVALUATION OF ALTERNATIVES

                     RINT  RINT  RINT JPR
CONTROL CARD 6       .010  .001  .100   1

                      LX  LI  LI  LI  LI  LI  LI   LY   LY   LY   LY   LY   LY  KX KCXX KCX KCX KCX KCX KCX KCX
CONTROL CARD 7        4   1   2   3   4   0   0   55   55   55   55    0    0   1    7   7   4   3   4   0   0

                     JXX  JX  JX  JX  JX  JX  JX NZZ  NZ  NZ  NZ  NZ  NZ  NZ IST  MX
CONTROL CARD 7       0   0   0   0   0   0   0   1   1   1   1   1   0   0   0   1

                                                          ROTATION LENGTH IN YEARS
          1                        2                        3                        4
         55                       55                       55                       55

PERIODIC COSTS AND INCOMES
 YEAR      COST       YEAR      COST       YEAR      COST       YEAR      COST       YEAR      COST       YEAR      COST
    0    -10.00          1    -19.00          1     -0.50          0     -9.00
    0    -20.00          2     -0.50         14     -0.50          1     -0.50
    1     -0.40         14     -0.50         15    -25.00         14     -0.50
    2     -0.50         15    -15.00          0         0         15    -22.00
   10     -4.00          0         0          0         0          0         0
   14     -0.50          0         0          0         0          0         0
   15    -25.00          0         0          0         0          0         0

                     K1XX  K1X  K1X  K1X  K1X  K1X  K1X
CONTROL CARD 11       3    3    1    1    1    0    0
                     K2XX  K2X  K2X  K2X  K2X  K2X  K2X
CONTROL CARD 11       0    0    0    0    0    0    0
                     K3XX  K3X  K3X  K3X  K3X  K3X  K3X
CONTROL CARD 11       0    0    0    0    0    0    0

PERIODIC RETURNS FROM SAWTIMBER MBF
  YEAR YIELD QUAL      YEAR YIELD QUAL      YEAR YIELD QUAL      YEAR YIELD QUAL      YEAR YIELD QUAL      YEAR YIELD QUAL
     1     4   50        55   350   80        55   310   70        55   310   70
    10    16   90         0     0    0         0     0    0         0     0    0
    55   280   70         0     0    0         0     0    0         0     0    0

 PRODUCT PRICES
             PRODUCT NO.1              PRODUCT NO.2              PRODUCT NO.3

        $   10.000  CH   .005
```

PROBLEM NO. 7A--COMPARISON OF TIMBER GROWING ALTERNATIVES--55 YEAR ROTATION

INTERNAL RATE OF RETURN FOR SCHEDULE 0001 IS BETWEEN 3.5 AND 3.6
WITH PRESENT WORTHS OF 1.42 AND -0.39 RESPECTIVELY.

INTERNAL RATE OF RETURN FOR SCHEDULE 0002 IS BETWEEN 4.8 AND 4.9
WITH PRESENT WORTHS OF .82 AND -0.44 RESPECTIVELY.

INTERNAL RATE OF RETURN FOR SCHEDULE 0003 IS BETWEEN 6.0 AND 6.1
WITH PRESENT WORTHS OF .10 AND -0.32 RESPECTIVELY.

INTERNAL RATE OF RETURN FOR SCHEDULE 0004 IS BETWEEN 4.8 AND 4.9
WITH PRESENT WORTHS OF .37 AND -0.55 RESPECTIVELY.

PRESENT DISCOUNTED NET WORTH AT GIVEN ALTERNATIVE RATES OF INTEREST

RATE	ALT-PLAN 1 (ROTATION 55)	ALT-PLAN 2 (ROTATION 55)	ALT-PLAN 3 (ROTATION 55)	ALT-PLAN 4 (ROTATION 55)	ALT-PLAN 0 (ROTATION 0)	ALT-PLAN 0 (ROTATION 0)
1.0	103.78	173.88	137.60	131.18		
1.1	96.34	163.15	129.45	122.99		
1.2	89.31	153.01	121.74	115.25		
1.3	82.67	143.43	114.46	107.94		
1.4	76.40	134.37	107.59	101.03		
1.5	70.47	125.80	101.10	94.50		
1.6	64.86	117.71	94.97	88.33		
1.7	59.57	110.05	89.17	82.50		
1.8	54.56	102.81	83.70	77.00		
1.9	49.83	95.97	78.54	71.80		
2.0	45.36	89.50	73.66	66.89		
2.1	41.13	83.38	69.05	62.25		
2.2	37.14	77.60	64.70	57.86		
2.3	33.37	72.13	60.59	53.72		
2.4	29.80	66.97	56.71	49.81		
2.5	26.43	62.08	53.04	46.12		
2.6	23.24	57.46	49.58	42.63		
2.7	20.23	53.09	46.32	39.33		
2.8	17.39	48.96	43.24	36.22		
2.9	14.70	45.06	40.33	33.28		
3.0	12.16	41.37	37.58	30.50		
3.1	9.76	37.88	34.99	27.88		
3.2	7.49	34.58	32.54	25.41		
3.3	5.35	31.47	30.23	23.07		
3.4	3.33	28.52	28.05	20.87		
3.5	1.42	25.73	26.00	18.79		
3.6	-0.39	23.10	24.06	16.82		
3.7	-2.10	20.61	22.23	14.97		
3.8	-3.71	18.26	20.51	13.22		
3.9	-5.23	16.04	18.88	11.57		
4.0	-6.67	13.94	17.35	10.01		
4.1	-8.03	11.96	15.90	8.55		
4.2	-9.31	10.08	14.54	7.16		
4.3	-10.52	8.31	13.26	5.85		
4.4	-11.66	6.64	12.05	4.62		
4.5	-12.74	5.06	10.91	3.46		
4.6	-13.76	3.56	9.84	2.37		
4.7	-14.72	2.15	8.83	1.34		
4.8	-15.63	.82	7.88	.37		

PRESENT DISCOUNTED NET WORTH AT GIVEN ALTERNATIVE RATES OF INTEREST

RATE	ALT-PLAN 1 (ROTATION 55)	ALT-PLAN 2 (ROTATION 55)	ALT-PLAN 3 (ROTATION 55)	ALT-PLAN 4 (ROTATION 55)	ALT-PLAN 0 (ROTATION 0)	ALT-PLAN 0 (ROTATION 0)
4.9	-16.49	-0.44	6.99	-0.55		
5.0	-17.30	-1.62	6.15	-1.41		
5.1	-18.06	-2.74	5.36	-2.22		
5.2	-18.78	-3.80	4.62	-2.98		
5.3	-19.46	-4.80	3.92	-3.70		
5.4	-20.10	-5.74	3.26	-4.37		
5.5	-20.70	-6.63	2.65	-5.01		
5.6	-21.27	-7.47	2.07	-5.60		
5.7	-21.80	-8.26	1.53	-6.16		
5.8	-22.31	-9.00	1.02	-6.69		
5.9	-22.78	-9.71	.55	-7.18		
6.0	-23.23	-10.37	.10	-7.65		
6.1	-23.65	-10.99	-0.32	-8.08		
6.2	-24.05	-11.58	-0.71	-8.49		
6.3	-24.42	-12.13	-1.07	-8.87		
6.4	-24.78	-12.65	-1.41	-9.23		
6.5	-25.11	-13.14	-1.73	-9.57		
6.6	-25.42	-13.60	-2.03	-9.88		
6.7	-25.71	-14.03	-2.31	-10.17		
6.8	-25.99	-14.44	-2.56	-10.45		
6.9	-26.24	-14.82	-2.80	-10.70		
7.0	-26.49	-15.18	-3.03	-10.94		
7.1	-26.71	-15.52	-3.23	-11.16		
7.2	-26.93	-15.84	-3.42	-11.37		
7.3	-27.13	-16.13	-3.60	-11.56		
7.4	-27.31	-16.41	-3.76	-11.74		
7.5	-27.49	-16.67	-3.91	-11.90		
7.6	-27.65	-16.92	-4.05	-12.05		
7.7	-27.81	-17.14	-4.18	-12.19		
7.8	-27.95	-17.36	-4.30	-12.32		
7.9	-28.09	-17.55	-4.40	-12.44		
8.0	-28.21	-17.74	-4.50	-12.55		
8.1	-28.33	-17.91	-4.59	-12.65		
8.2	-28.44	-18.07	-4.67	-12.75		
8.3	-28.54	-18.22	-4.74	-12.83		
8.4	-28.63	-18.36	-4.80	-12.91		
8.5	-28.72	-18.49	-4.86	-12.98		
8.6	-28.80	-18.61	-4.91	-13.04		
8.7	-28.88	-18.72	-4.95	-13.10		
8.8	-28.95	-18.82	-4.99	-13.15		
8.9	-29.02	-18.91	-5.03	-13.19		
9.0	-29.08	-19.00	-5.05	-13.23		
9.1	-29.13	-19.08	-5.08	-13.26		
9.2	-29.18	-19.15	-5.09	-13.29		
9.3	-29.23	-19.21	-5.11	-13.32		
9.4	-29.27	-19.27	-5.12	-13.34		
9.5	-29.31	-19.33	-5.12	-13.36		
9.6	-29.35	-19.38	-5.13	-13.37		
9.7	-29.38	-19.42	-5.13	-13.38		
9.8	-29.41	-19.46	-5.12	-13.39		
9.9	-29.43	-19.49	-5.12	-13.39		
10.0	-29.46	-19.52	-5.11	-13.39		

PROBLEM NO. 78--COMPARISON OF TIMBER GROWING ALTERNATIVES--85 YEAR ROTATION ID= 0

GENERAL EVALUATION OF ALTERNATIVES

	RINT	RINT	RINT	JPR
CONTROL CARD 6	.010	.001	.100	1

	LX	LI	LI	LI	LI	LI	LI	LY	LY	LY	LY	LY	LY	KX	KCXX	KCX	KCX	KCX	KCX	KCX	KCX
CONTROL CARD 7	4	1	2	3	4	0	0	85	85	85	85	0	0	1	7	7	4	3	4	0	0

	JXX	JX	JX	JX	JX	JX	JX	NZZ	NZ	NZ	NZ	NZ	NZ	NZ	IST	MX
CONTROL CARD 7	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	1

ROTATION LENGTH IN YEARS

1	2	3	4
85	85	85	85

PERIODIC COSTS AND INCOMES

YEAR	COST	YEAR	COST	YEAR	COST	YEAR	COST	YEAR	COST	YEAR	COST
0	-10.00	1	-19.00	1	-0.50	0	-9.00				
0	-20.00	2	-0.50	14	-0.50	1	-0.50				
1	-0.40	14	-0.50	15	-25.00	14	-0.50				
2	-0.50	15	-15.00	0	0	15	-22.00				
10	-4.00	0	0	0	0	0	0				
14	-0.50	0	0	0	0	0	0				
15	-25.00	0	0	0	0	0	0				

	K1XX	K1X	K1X	K1X	K1X	K1X	K1X
CONTROL CARD 11	4	4	2	2	2	0	0

	K2XX	K2X	K2X	K2X	K2X	K2X	K2X
CONTROL CARD 11	0	0	0	0	0	0	0

	K3XX	K3X	K3X	K3X	K3X	K3X	K3X
CONTROL CARD 11	0	0	0	0	0	0	0

PERIODIC RETURNS FROM SAWTIMBER MBF

YEAR	YIELD	QUAL	YEAR	YIELD	QUAL	YEAR	YIELD	QUAL	YEAR	YIELD	QUAL	YEAR	YIELD	QUAL	YEAR	YIELD	QUAL
1	4	50	50	100	60	50	90	50	50	90	50						
10	16	90	85	700	100	85	680	95	85	680	95						
50	80	50	0	0	0	0	0	0	0	0	0						
85	650	95	0	0	0	0	0	0	0	0	0						

PRODUCT PRICES

PRODUCT NO.1	PRODUCT NO.2	PRODUCT NO.3
$ 10.000 CH .005		

PROBLEM NO. 7B--COMPARISON OF TIMBER GROWING ALTERNATIVES--85 YEAR ROTATION

INTERNAL RATE OF RETURN FOR SCHEDULE 0001 IS BETWEEN 4.1 AND 4.2
WITH PRESENT WORTHS OF .18 AND -2.27 RESPECTIVELY.

INTERNAL RATE OF RETURN FOR SCHEDULE 0002 IS BETWEEN 4.7 AND 4.8
WITH PRESENT WORTHS OF 1.26 AND -0.53 RESPECTIVELY.

INTERNAL RATE OF RETURN FOR SCHEDULE 0003 IS BETWEEN 5.7 AND 5.8
WITH PRESENT WORTHS OF .20 AND -0.44 RESPECTIVELY.

INTERNAL RATE OF RETURN FOR SCHEDULE 0004 IS BETWEEN 4.9 AND 5.0
WITH PRESENT WORTHS OF .46 AND -0.85 RESPECTIVELY.

PRESENT DISCOUNTED NET WORTH AT GIVEN ALTERNATIVE RATES OF INTEREST

RATE	ALT-PLAN 1 (ROTATION 85)	ALT-PLAN 2 (ROTATION 85)	ALT-PLAN 3 (ROTATION 85)	ALT-PLAN 4 (ROTATION 85)	ALT-PLAN 0 (ROTATION 0)	ALT-PLAN 0 (ROTATION 0)
1.0	367.29	441.10	406.86	400.44		
1.1	335.58	404.57	373.66	367.20		
1.2	306.42	370.96	343.13	336.64		
1.3	279.60	340.04	315.06	308.53		
1.4	254.94	311.59	289.24	282.68		
1.5	232.25	285.40	265.50	258.90		
1.6	211.38	261.30	243.67	237.03		
1.7	192.19	239.11	223.58	216.91		
1.8	174.52	218.68	205.11	198.40		
1.9	158.27	199.87	188.11	181.37		
2.0	143.31	182.54	172.47	165.70		
2.1	129.55	166.59	158.08	151.28		
2.2	116.88	151.89	144.84	138.00		
2.3	105.21	138.35	132.65	125.79		
2.4	94.47	125.88	121.44	114.54		
2.5	84.59	114.39	111.12	104.19		
2.6	75.49	103.79	101.62	94.66		
2.7	67.10	94.03	92.87	85.88		
2.8	59.38	85.03	84.82	77.81		
2.9	52.28	76.74	77.41	70.37		
3.0	45.73	69.09	70.59	63.52		
3.1	39.69	62.04	64.31	57.21		
3.2	34.14	55.54	58.53	51.40		
3.3	29.02	49.55	53.21	46.05		
3.4	24.30	44.02	48.31	41.13		
3.5	19.96	38.92	43.80	36.59		
3.6	15.95	34.22	39.65	32.41		
3.7	12.26	29.88	35.83	28.57		
3.8	8.86	25.87	32.31	25.02		
3.9	5.73	22.18	29.07	21.76		
4.0	2.84	18.77	26.09	18.76		
4.1	.18	15.63	23.35	15.99		
4.2	-2.27	12.73	20.82	13.44		
4.3	-4.53	10.05	18.50	11.09		
4.4	-6.62	7.58	16.36	8.93		
4.5	-8.54	5.30	14.40	6.95		
4.6	-10.31	3.20	12.59	5.12		
4.7	-11.94	1.26	10.93	3.43		
4.8	-13.44	-0.53	9.40	1.88		

PRESENT DISCOUNTED NET WORTH AT GIVEN ALTERNATIVE RATES OF INTEREST

RATE	ALT-PLAN 1 (ROTATION 85)	ALT-PLAN 2 (ROTATION 85)	ALT-PLAN 3 (ROTATION 85)	ALT-PLAN 4 (ROTATION 85)	ALT-PLAN 0 (ROTATION 0)	ALT-PLAN 0 (ROTATION 0)
4.9	-14.82	-2.18	7.99	.46		
5.0	-16.10	-3.71	6.70	-0.85		
5.1	-17.28	-5.11	5.52	-2.06		
5.2	-18.36	-6.41	4.43	-3.17		
5.3	-19.36	-7.61	3.43	-4.18		
5.4	-20.27	-8.71	2.52	-5.12		
5.5	-21.12	-9.73	1.68	-5.98		
5.6	-21.90	-10.66	.91	-6.77		
5.7	-22.62	-11.53	.20	-7.49		
5.8	-23.27	-12.32	-0.44	-8.15		
5.9	-23.88	-13.06	-1.03	-8.76		
6.0	-24.44	-13.73	-1.57	-9.32		
6.1	-24.95	-14.35	-2.06	-9.83		
6.2	-25.42	-14.93	-2.51	-10.29		
6.3	-25.86	-15.45	-2.92	-10.72		
6.4	-26.26	-15.94	-3.29	-11.11		
6.5	-26.62	-16.38	-3.63	-11.46		
6.6	-26.96	-16.79	-3.93	-11.78		
6.7	-27.26	-17.16	-4.21	-12.07		
6.8	-27.55	-17.50	-4.46	-12.34		
6.9	-27.80	-17.82	-4.68	-12.58		
7.0	-28.04	-18.11	-4.89	-12.80		
7.1	-28.25	-18.37	-5.07	-13.00		
7.2	-28.45	-18.61	-5.23	-13.17		
7.3	-28.63	-18.83	-5.37	-13.33		
7.4	-28.79	-19.03	-5.50	-13.47		
7.5	-28.94	-19.21	-5.61	-13.60		
7.6	-29.08	-19.37	-5.71	-13.71		
7.7	-29.20	-19.52	-5.80	-13.81		
7.8	-29.31	-19.65	-5.87	-13.90		
7.9	-29.41	-19.77	-5.93	-13.98		
8.0	-29.50	-19.88	-5.99	-14.04		
8.1	-29.58	-19.98	-6.03	-14.10		
8.2	-29.66	-20.07	-6.07	-14.15		
8.3	-29.72	-20.14	-6.09	-14.19		
8.4	-29.78	-20.21	-6.11	-14.22		
8.5	-29.83	-20.27	-6.13	-14.24		
8.6	-29.88	-20.32	-6.13	-14.26		
8.7	-29.92	-20.36	-6.13	-14.28		
8.8	-29.95	-20.40	-6.13	-14.28		
8.9	-29.98	-20.43	-6.12	-14.29		
9.0	-30.01	-20.45	-6.11	-14.29		
9.1	-30.03	-20.47	-6.09	-14.28		
9.2	-30.05	-20.49	-6.07	-14.27		
9.3	-30.06	-20.50	-6.05	-14.26		
9.4	-30.07	-20.50	-6.02	-14.24		
9.5	-30.08	-20.51	-5.99	-14.22		
9.6	-30.09	-20.50	-5.96	-14.20		
9.7	-30.09	-20.50	-5.93	-14.18		
9.8	-30.09	-20.49	-5.89	-14.15		
9.9	-30.09	-20.48	-5.85	-14.12		
10.0	-30.09	-20.47	-5.81	-14.09		

Figure 21. – Investment Analysis Program No. 6.

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                                        31/32/3300 FORTRAN (2.1)/MSOS   02/02/68

      PROGRAM INVEST6                                                          INV  10
C  INVESTMENT ANALYSIS PROGRAM--DECEMBER 1967                                 INV  20
C                                                                            INV  30
C  J. H. WIKSTROM                                                            INV  40
C  INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION                         INV  50
C                                                                            INV  60
C  THIS PROGRAM IS AN ADAPTATION OF CLARK ROW#S INVEST PROGRAM               INV  70
C  IT CAN BE USED WITH OR WITHOUT PRODUCT VALUES                             INV  80
C  IT HANDLES BOTH PERIODIC AND ANNUAL COSTS AND INCOMES                  I  INV  90
C  EXTRA CONTROL CARDS ARE NEEDED FOR PRODUCT RETURNS                        INV 100
C  FINAL VALUE IS HANDLED AS A PERIODIC INCOME                               INV 110
C                                                                            INV 120
C  PROGRAM CONTAINS 3 OPTIONS---                                             INV 130
C        GENERAL OPTION FOR INTERNAL RATE OF RETURN-PRESENT WORTH            INV 140
C        OPTION FOR STAND REPLACEMENT PRIORITIES                             INV 150
C        OPTION TO EVALUATE TIMBER STAND IMPROVEMENT ALTERNATIVES            INV 160
C                                                                            INV 170
C  RE-ROW--USFS RESEARCH PAPER  SO-6                                         INV 180
C  RE-MARTY, ETAL--USDA HANDBOOK 304                                         INV 190
C                                                                            INV 200
C                                                                            INV 210
      DIMENSION AN(6,4),CAN(6,4),NC(6,100),PECO(6,100),N1(6,100),JLD1(6,     INV 220
     150),JUAL1(6,50),N2(6,100),JLD2(6,50),JUAL2(6,50),N3(6,100),JLD3(6,     INV 230
     250),JUAL3(6,50),PR(3,3),CPR(3,3),FVAL(6,1),RATE(100),RTLOG(100),       INV 240
     3VALIN(6,100),FCROP(6,100),LY(6),KCX(6),K1X(6),K2X(6),K3X(6),NZ(6)      INV 250
      DIMENSION NI(6,4),NT(6,4),A(12),LI(6),JX(6,10),RINT(3),NAME(20)        INV 260
      DIMENSION IDEN(20)                                                     INV 270
C                                                                            INV 280
C  FORMATS USED                                                              INV 290
C                                                                            INV 300
   10 FORMAT (8A4)                                                           INV 310
   11 FORMAT(19H1NATIONAL FOREST    ,8A4)                                    INV 320
   12 FORMAT(8HOUNIT - ,8A4)                                                 INV 330
   13 FORMAT(13HOATTENTION - ,8A4/1H-)                                       INV 340
   14 FORMAT(1HO,38X,44HINVESTMENT ANALYSIS PROGRAM NO.6,  INT. STA.,/)      INV 350
   15 FORMAT(19A4,2X,I2)                                                     INV 360
   16 FORMAT(15HOPROBLEM NO.    ,19A4,4X,4HID= ,I2,/1H-)                     INV 370
   17 FORMAT(20A4)                                                           INV 380
   18 FORMAT (1HO4X,20A4)                                                    INV 390
   19 FORMAT(3F4.3, I2)                                                      INV 400
   20 FORMAT(1HO,44X,34HGENERAL EVALUATION OF ALTERNATIVES)                  INV 410
   21 FORMAT(1HO,40X,42HEVALUATION OF STAND REPLACEMENT PRIORITIES)          INV 420
   22 FORMAT(1HO,38X,47HEVALUATION OF TIMBER STAND IMPROVEMENT PROGRAMS)     INV 430
   23 FORMAT(1HO,16X,3(2X4HRINT),1X,3HJPR)                                   INV 440
   24 FORMAT(17HOCONTROL CARD 6  ,3(F6.3),2X,I2)                             INV 450
   25 FORMAT(37HOCONTROL CARDS FOR FUTURE STANDS*****)                       INV 460
   26 FORMAT(38HOCONTROL CARDS FOR FIRST TSI PLAN*****)                      INV 470
   27 FORMAT(7I2,6I3,24I2)                                                   INV 480
   28 FORMAT(1H016X,2HLX,6(2X,2HLI),6(3X,2HLY),2X,2HKX,1X,4HKCXX,6(1X,       INV 490
     13HKCX))                                                                INV 500
   29 FORMAT(17HMCONTROL CARD 7  ,I2,6(2X,I2),6(2X,I3),2X,I2,3X,I2,6(2X,    INV 510
     1I2))                                                                   INV 520
   30 FORMAT(1H015X,3HJXX,6(2X,2HJX),1X,3HNZZ,6(2X,2HNZ),1X,3HIST,2X,        INV 530
     12HMX)                                                                  INV 540
   31 FORMAT(17HMCONTROL CARD 7  ,  I2,15(2X,I2))                            INV 550
   32 FORMAT(1HO,49X,24HROTATION LENGTH IN YEARS)                            INV 560
   33 FORMAT (8X,I3,5(17X,I3))                                               INV 570
   34 FORMAT(27HOPERIODIC COSTS AND INCOMES,/2X,6(14HYEAR       COST,6X))    INV 580
   35  FORMAT(6(I3,F9.2)  )                                                  INV 590
   36 FORMAT (2X,6(I4,1X,F9.2,6X))                                           INV 600
   37 FORMAT(4(2I3,F8.2,F6.3))                                               INV 610
   38 FORMAT(      39HOANNUAL COSTS AND RETURNS--ALT. OR PLAN,I4)            INV 620
   39 FORMAT(10X,8H1ST YEAR,1XI3,2X,8HEND YEAR,1X,I3,2X,1H$,F9.2,2X,6HCH     INV 630
     1ANGE,F7.3)                                                             INV 640
   40 FORMAT(41HONO ANNUAL COSTS OR RETURNS--ALT. OR PLAN,I4)                INV 650
   41 FORMAT(21I2)                                                           INV 660
   42 FORMAT(1H017X,4HK1XX,6(2X,3HK1X))                                      INV 670
   43 FORMAT(17HMCONTROL CARD 11 ,12(2X,I3))                                 INV 680
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   44 FORMAT(1HO17X,4HK2XX,6(2X,3HK2X))                                    INV 690
   45 FORMAT(1HO17X,4HK3XX,6(2X,3HK3X))                                    INV 700
   46 FORMAT(14A5)                                                         INV 710
   47 FORMAT(23H0PERIODIC RETURNS FROM ,4A5)                               INV 720
   48 FORMAT(1HO,2X,6(15HYEAR YIELD QUAL,5X))                              INV 730
   49 FORMAT (6(I3,I5,I4))                                                 INV 740
   50 FORMAT(I7,I6,I5,5(I9,I6,I5))                                         INV 750
   51 FORMAT(16H0 PRODUCT PRICES)                                          INV 760
   52 FORMAT(14X,12HPRODUCT NO.1,14X,12HPRODUCT NO.2,14X12HPRODUCT NO.3,   INV 770
     1/)                                                                   INV 780
   53 FORMAT(6(F9.3))                                                      INV 790
   54 FORMAT(1HO( 8X,1H$,F9.3,2X,2HCH,F7.3))                               INV 800
   55 FORMAT(1HO7X,6(9X,9HALT-PLAN ,I2))                                   INV 810
   58 FORMAT(1H036HDISCOUNTED NET WORTH OF FUTURE CROPS)                   INV 820
   59 FORMAT(1H139HCONTROL CARDS 7* FOR PRESENT STAND*****)                INV 830
   60 FORMAT(1H048HDISCOUNTED NET WORTH OF PRESENT AND FUTURE CROPS)       INV 840
   65 FORMAT(1H1,12HPROBLEM NO. ,19A4,/)                                   INV 850
   66 FORMAT (1HO,37HINTERNAL RATE OF RETURN FOR SCHEDULE ,A4,12H IS BET   INV 860
     1WEEN ,F5.1,5H AND ,F5.1/1H ,23HWITH PRESENT WORTHS OF ,F6.2,5H AND   INV 870
     2 ,F6.2,15H RESPECTIVELY.       )                                     INV 880
   67 FORMAT(1HO,37HINTERNAL RATE OF RETURN FOR SCHEDULE ,A4,32H IS NOT    INV 890
     1INCLUDED IN THE PROBLEM.)                                            INV 900
   68 FORMAT(1HO,37HINTERNAL RATE OF RETURN FOR SCHEDULE ,A4,4H IS ,F7.    INV 910
     11/)                                                                  INV 920
   69 FORMAT(1H02X,67HPRESENT DISCOUNTED NET WORTH AT GIVEN ALTERNATIVE    INV 930
     1RATES OF INTEREST)                                                   INV 940
   70 FORMAT (8HO   RATE,6(6X,10H(ROTATION ,I3,1H))/)                      INV 950
   72 FORMAT (1H ,F7.1,6F20.2)                                             INV 960
   75 FORMAT(1H036HDISCOUNTED NET WORTH--FIRST TSI PLAN)                   INV 970
   76 FORMAT(1H141HCONTROL CARDS 7* FOR SECOND TSI PLAN*****)              INV 980
   77 FORMAT(1H037HDISCOUNTED NET WORTH--SECOND TSI PLAN)                  INV 990
   78 FORMAT(1H044HDISCOUNTED NET WORTH OF ADDED TSI INVESTMENT)           INV1000
   99 FORMAT(23HO  ERROR IN INPUT CARDS )                                  INV1010
  610 FORMAT(1H1)                                                          INV1020
C                                                                          INV1030
C                                                                          INV1040
C                                                                          INV1050
C  READ NAME OF NATIONAL FOREST OR ORGANIZATION                            INV1060
    1 READ (60,10)(NAME(I),I=1,8)                                          INV1070
      WRITE (61,11)(NAME(I),I=1,8)                                         INV1080
C                                                                          INV1090
C  READ NAME OF UNIT                                                       INV1100
      READ(60,10)(NAME(I),I=1,8)                                           INV1110
      WRITE(61,12)(NAME(I),I=1,8)                                          INV1120
C                                                                          INV1130
C  READ NAME OF USER                                                       INV1140
      READ (60,10)(NAME(I),I=1,8)                                          INV1150
      WRITE (61,13)(NAME(I),I=1,8)                                         INV1160
      WRITE (61,14)                                                        INV1170
C                                                                          INV1180
C  READ CARD 4, PROBLEM TITLE                                              INV1190
  100 READ (60,15)(NAME(I),I=1,19),ID                                      INV1200
      GO TO (910,105)EOFCKF(60)                                            INV1210
  105 IF(NAME(1).EQ.4HNEW )1,106                                           INV1220
  106 WRITE(61,16)(NAME(I),I=1,19),ID                                      INV1230
C                                                                          INV1240
C  READ CARD 5, PROBLEM DESCRIPTION CARDS                                  INV1250
      IF(ID.GT.0)107,110                                                   INV1260
  107 DO 109  J=1,ID                                                       INV1270
      READ(60,17)(IDEN(I),I=1,20)                                          INV1280
  109 WRITE(61,18)(IDEN(I),I=1,20)                                         INV1290
C                                                                          INV1300
C  CONTROL CARD 6, INTEREST RATES AND PROGRAM OPTION                       INV1310
  110 READ(60,19)(RINT(I),I=1,3),JPR                                       INV1320
      IF (JPR-2)111,112,113                                                INV1330
  111 WRITE(61,20)                                                         INV1340
      GO TO 114                                                            INV1350
  112 WRITE(61,21)                                                         INV1360
      GO TO 114                                                            INV1370
  113 WRITE(61,22)                                                         INV1380
  114 WRITE(61,23)                                                         INV1390
      WRITE(61,24)(RINT(I),I=1,3),JPR                                      INV1400
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C                                                                       INV1410
C  READ CARD 7,  GENERAL CONTROL CARD                                   INV1420
      IF(JPR-2)1000,115,116                                             INV1430
  115 WRITE(61,25)                                                      INV1440
      GO TO 1000                                                        INV1450
  116 WRITE(61,26)                                                      INV1460
 1000 READ(60,27)   LX,(LI(L),L=1,6),(LY(L),L=1,6),KX,KCXX,(KCX(L),L=1,6 INV1470
     1),JXX,(JX(L),L=1,6),NZZ,(NZ(L),L=1,6),IST,MX                      INV1480
      WRITE(61,28)                                                      INV1490
      WRITE(61,29)LX,(LI(L),L=1,6),(LY(L),L=1,6),KX,KCXX,(KCX(L),L=1,6) INV1500
      WRITE(61,30)                                                      INV1510
      WRITE(61,31)JXX,(JX(L),L=1,6),NZZ,(NZ(L),L=1,6),IST,MX            INV1520
      WRITE(61,32)                                                      INV1530
      WRITE(61, 33) (LI(L), L=1,LX)                                     INV1540
      WRITE(61,33)(LY(L),L=1,LX)                                        INV1550
      IF (KCXX) 135,135,120                                             INV1560
  120 WRITE(61,34)                                                      INV1570
C                                                                       INV1580
C  READ CARD 8, PERIODIC COSTS AND INCOMES                              INV1590
      DO 130 KC=1,KCXX                                                  INV1600
      READ(60,35)(NC(L,KC),PECO(L,KC),L=1,6)                            INV1610
  130 WRITE(61,36)(NC(L,KC), PECO(L,KC),L=1,LX)                         INV1620
C                                                                       INV1630
C  READ CARD 9,  ANNUAL COSTS AND INCOMES                               INV1640
  135 IF (JXX) 140,140,136                                              INV1650
  136 DO 140 L=1,LX                                                     INV1660
      IF (JX(L))138,138,137                                             INV1670
  137 JXL=JX(L)                                                         INV1680
      LIL=LI(L)                                                         INV1690
      READ(60,37)(NI(L,I2),NT(L,I2),AN(L,I2),CAN(L,I2),I2=1,JXL)        INV1700
      WRITE(61,38) LIL                                                  INV1710
      WRITE(61,39)(NI(L,I2),NT(L,I2),AN(L,I2),CAN(L,I2),I2=1,JXL)       INV1720
      GO TO 140                                                         INV1730
  138 WRITE(61,40) LIL                                                  INV1740
  140 CONTINUE                                                          INV1750
C                                                                       INV1760
C  READ CARD 10,  PRODUCT EVALUATION CONTROL CARD                       INV1770
      IF (KX) 200,200,150                                               INV1780
  150 READ(60,41)K1XX,(K1X(L),L=1,6),K2XX,(K2X(L),L=1,6),K3XX,(K3X(L),  INV1790
     1L=1,6)                                                            INV1800
      WRITE(61,42)                                                      INV1810
      WRITE(61,43)K1XX,(K1X(L),L=1,6)                                   INV1820
      WRITE(61,44)                                                      INV1830
      WRITE(61,43)K2XX,(K2X(L),L=1,6)                                   INV1840
      WRITE(61,45)                                                      INV1850
      WRITE(61,43)K3XX,(K3X(L),L=1,6)                                   INV1860
C                                                                       INV1870
C  READ CARD 11,  PRODUCT NAMES                                         INV1880
      READ(60,46)(A(I),I=1,12)                                          INV1890
      IF (K1XX) 170,170,162                                             INV1900
  162 WRITE(61,47)(A(I),I= 1,4)                                         INV1910
      WRITE(61,48)                                                      INV1920
C                                                                       INV1930
C  READ CARD 12,  PRODUCT 1 RETURNS                                     INV1940
      DO 165 K1= 1,K1XX                                                 INV1950
      READ(60,49)(N1(L,K1),JLD1(L,K1),JUAL1(L,K1),L=1,6)                INV1960
  165 WRITE(61,50)  (N1(L,K1),JLD1(L,K1),JUAL1(L,K1), L=1,LX)           INV1970
  170 IF(K2XX) 180,180,172                                              INV1980
  172 WRITE(61,47)(A(I),I=5,8)                                          INV1990
      WRITE(61,48)                                                      INV2000
C                                                                       INV2010
C  READ CARD 12,  PRODUCT 2 RETURNS                                     INV2020
      DO 175 K2=1,K2XX                                                  INV2030
      READ(60,49)(N2(L,K2),JLD2(L,K2),JUAL2(L,K2),L=1,6)                INV2040
  175 WRITE(61,50)(N2(L,K2),JLD2(L,K2),JUAL2(L,K2),L=1,LX)              INV2050
  180 IF (K3XX) 190,190,182                                             INV2060
  182 WRITE(61,47)(A(I), I=9,12)                                        INV2070
      WRITE(61,48)                                                      INV2080
C                                                                       INV2090
C  READ CARD 12,  PRODUCT 3 RETURNS                                     INV2100
      DO 185 K3=1,K3XX                                                  INV2110
      READ(60,49)(N3(L,K3),JLD3(L,K3),JUAL3(L,K3),L=1,6)                INV2120
  185 WRITE(61,50)(N3(L,K3),JLD3(L,K3),JUAL3(L,K3),L=1,LX)              INV2130
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  190 CONTINUE                                                          INV2140
C                                                                       INV2150
C  READ CARD 13,  PRODUCT PRICES                                        INV2160
      WRITE(61,51)                                                      INV2170
      WRITE(61,52)                                                      INV2180
      DO 197 M=1,MX                                                     INV2190
      READ(60,53)(PR(K,M),CPR(K,M),K=1,KX)                              INV2200
      WRITE(61,54)(PR(K,M),CPR(K,M),K=1,KX)                             INV2210
  197 CONTINUE                                                          INV2220
  200 CONTINUE                                                          INV2230
C                                                                       INV2240
C     BEGIN PROCESSING DATA.                                            INV2250
C                                                                       INV2260
      RATE(1)=RINT(1)                                                   INV2270
      DO 210 I=2,100                                                    INV2280
      IF(RATE(I-1)-RINT(3))202,203,203                                  INV2290
  202 RATE(I)=RATE(I-1)+RINT(2)                                         INV2300
      GO TO 210                                                         INV2310
  203 LENGTH=I-1                                                        INV2320
      IF(LENGTH-(LENGTH/2)*2)204,205,204                                INV2330
  204 LLNGTH=(LENGTH +1)/2                                              INV2340
      GO TO 215                                                         INV2350
  205 LLNGTH=LENGTH/2                                                   INV2360
      GO TO 215                                                         INV2370
  210 CONTINUE                                                          INV2380
  215 DO 216 I=1,LENGTH                                                 INV2390
  216 RTLOG(I)=1.+RATE(I)                                               INV2400
C                                                                       INV2410
C     DO COMPUTATIONS                                                   INV2420
C                                                                       INV2430
      IF (KX)218,218,217                                                INV2440
  217 DO 600 M=1,MX                                                     INV2450
  218 DO 300 L=1,LX                                                     INV2460
      DO 300 I=1,LENGTH                                                 INV2470
      KCXA=KCX(L)                                                       INV2480
      K1XA=K1X(L)                                                       INV2490
      K2XA=K2X(L)                                                       INV2500
      K3XA=K3X(L)                                                       INV2510
      DAN=DCAN=0.0                                                      INV2520
      DKC= 0.0                                                          INV2530
      DK1=DK2=DK3=0.0                                                   INV2540
      RTLOI=RTLOG(I)                                                    INV2550
      LYL= LY(L)                                                        INV2560
      DISCO=RTLOI**LYL                                                  INV2570
C                                                                       INV2580
C  COMPUTE DISCOUNTED PERIODIC COSTS AND INCOMES                        INV2590
C                                                                       INV2600
      IF (KCXX)226,226,220                                              INV2610
  220 IF(KCXA)226,226,221                                               INV2620
  221 DO 225 KC=1,KCXA                                                  INV2630
      KXLY=NC(L,KC)                                                     INV2640
      DISC=RTLOI ** KXLY                                                INV2650
  225 DKC=DKC+PECO(L,KC)/DISC                                           INV2660
C                                                                       INV2670
C  COMPUTE DISCOUNTED ANNUAL COSTS AND INCOMES                          INV2680
C                                                                       INV2690
  226 IF (JXX)240,240,230                                               INV2700
  230 IF (JX(L))240,240,231                                             INV2710
  231 JXL=JX(L)                                                         INV2720
      DO 240 I2=1,JXL                                                   INV2730
      NTL=(NT(L,I2)-NI(L,I2))                                           INV2740
      NIL= NI(L,I2)                                                     INV2750
      IF(AN(L,I2))232,240,232                                           INV2760
  232 SISCO= RTLOI**NTL                                                 INV2770
      FISCO= RTLOI**NIL                                                 INV2780
      BBN=(AN(L,I2)*(SISCO-1.))/(RATE(I)*SISCO)                         INV2790
      IF(NIL.GT.0)233,234                                               INV2800
  233 BAN=(BBN/(RATE(I)*FISCO))                                         INV2810
      GO TO 235                                                         INV2820
  234 BAN= BBN                                                          INV2830
  235 DAN= DAN + BAN                                                    INV2840
      IF(CAN(L,I2)) 236,240,236                                         INV2850
  236 CCAN=(CAN(L,I2)*AN(L,I2)*(SISCO-NTL * RATE(I)-1.))/(RATE(I)**2*SISCO INV2860
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     1)                                                                 INV2870
      IF(NIL.GT.0) 237,238                                              INV2880
  237 BCAN=(CCAN/(RATE(I)*FISCO))                                       INV2890
      GO TO 239                                                         INV2900
  238 BCAN= CCAN                                                        INV2910
  239 DCAN= DCAN + BCAN                                                 INV2920
  240 CONTINUE                                                          INV2930
C                                                                       INV2940
C  COMPUTE DISCOUNTED PRODUCT VALUES                                    INV2950
C                                                                       INV2960
      IF (KX)280,280,250                                                INV2970
  250 IF (K1XA) 260,260,251                                             INV2980
  251 DO 255 K1=1,K1XA                                                  INV2990
      KXLY=N1(L,K1)                                                     INV3000
      QUAL1=JUAL1(L,K1) * .01                                           INV3010
      DISC=RTLOI ** KXLY                                                INV3020
      YLD1=JLD1(L,K1) * .1                                              INV3030
  255 DK1=DK1+(YLD1*PR(1,M)*QUAL1*(1.+CPR(1,M)*N1(L,K1))/DISC)          INV3040
  260 IF (K2XA)270,270,261                                              INV3050
  261 DO 265 K2=1,K2XA                                                  INV3060
      KXLY=N2(L,K2)                                                     INV3070
      DISC=RTLOI ** KXLY                                                INV3080
      QUAL2=JUAL2(L,K2) * .01                                           INV3090
      YLD2=JLD2(L,K2) * .1                                              INV3100
  265 DK2=DK2+(YLD2*PR(2,M)*QUAL2*(1.+CPR(2,M)*N2(L,K2))/DISC)          INV3110
  270 IF(K3XA)280,280,271                                               INV3120
  271 DO 275 K3=1,K3XA                                                  INV3130
      KXLY=N3(L,K3)                                                     INV3140
      DISC=RTLOI ** KXLY                                                INV3150
      QUAL3=JUAL3(L,K3) * .01                                           INV3160
      YLD3=JLD3(L,K3) * .1                                              INV3170
  275 DK3=DK3+(YLD3*PR(3,M)*QUAL3*(1.+CPR(3,M)*N3(L,K3))/DISC)          INV3180
C                                                                       INV3190
C  SUMMARIZE (FILL VALIN ARRAY)                                         INV3200
C                                                                       INV3210
  280 IF (NZZ)295,295,290                                               INV3220
  290 IF (NZ(L))295,295,292                                             INV3230
  292 TDVAL=DK1+DK2+DK3+ DAN+ DCAN+ DKC                                 INV3240
      VALIN(L,I)=TDVAL                                                  INV3250
      GO TO 300                                                         INV3260
  295 TDVAL=DK1+DK2+DK3+ DAN+ DCAN+DKC                                  INV3270
      VALIN(L,I)=TDVAL*( 1.+ 1. /(DISCO-1.))                            INV3280
  300 CONTINUE                                                          INV3290
C                                                                       INV3300
      IF (JPR-2)303,302,301                                             INV3310
  301 GO TO 400                                                         INV3320
  302 GO TO 350                                                         INV3330
  303 CONTINUE                                                          INV3340
C                                                                       INV3350
C  COMPLETE OUTPUT FOR GENERAL OPTION                                   INV3360
C                                                                       INV3370
      WRITE(61,65) (NAME(I),I=1,19)                                     INV3380
      DO 304 I=1,LENGTH                                                 INV3390
      RATE (I)= RATE(I)*100.0                                           INV3400
  304 CONTINUE                                                          INV3410
      DO 320 L=1,LX                                                     INV3420
      DO 310 I=1,LENGTH                                                 INV3430
      IF (VALIN(L,I).GT.0.0)310,305                                     INV3440
  305 IF (VALIN(L,I).EQ.0.0)308,306                                     INV3450
  306 IF (I.EQ.1)311,307                                                INV3460
  307 WRITE(61,66)LI(L),RATE(I-1),RATE(I),VALIN(L,I-1),VALIN(L,I)       INV3470
      GO TO 320                                                         INV3480
  308 WRITE(61,68) LI(L),RATE(I)                                        INV3490
      GO TO 320                                                         INV3500
  310 CONTINUE                                                          INV3510
  311 WRITE(61,67)     LI(L)                                            INV3520
  320 CONTINUE                                                          INV3530
      WRITE(61,69)                                                      INV3540
      WRITE(61,55)(LI(L),L=1,6)                                         INV3550
      WRITE(61,70) (LY(L),L=1,6)                                        INV3560
      DO 321 I=1,LENGTH                                                 INV3570
      WRITE(61,72)RATE(I),(VALIN(L,I),L=1,LX)                           INV3580
  321 CONTINUE                                                          INV3590
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      DO 325 I=1,LENGTH                                                 INV3600
      RATE (I)=RATE(I)/100.0                                            INV3610
  325 CONTINUE                                                          INV3620
      GO TO 600                                                         INV3630
C                                                                       INV3640
C  CONTINUE WITH PROGRAM OPTION 2                                       INV3650
C                                                                       INV3660
  350 IF(IST.EQ.1)351,360                                               INV3670
  351 DO 355 L=1,LX                                                     INV3680
      DO 355 I=1,LENGTH                                                 INV3690
  355 FCROP(L,I)=VALIN(L,I)                                             INV3700
      VALIN(L,I)=0.0                                                    INV3710
      WRITE(61,65) (NAME(I),I=1,19)                                     INV3720
      WRITE(61,58)                                                      INV3730
      DO 356 I=1,LENGTH                                                 INV3740
  356 RATE (I)=RATE(I)*100.0                                            INV3750
      WRITE(61,55)(LI(L),L=1,6)                                         INV3760
      WRITE(61,70)(LY(L),L=1,6)                                         INV3770
      DO 357 I=1,LENGTH                                                 INV3780
      WRITE (61,72) RATE(I),(FCROP(L,I),L=1,LX)                         INV3790
  357 CONTINUE                                                          INV3800
      DO 358 I=1,LENGTH                                                 INV3810
      RATE (I)= RATE(I)/100.0                                           INV3820
  358 CONTINUE                                                          INV3830
      WRITE(61,59)                                                      INV3840
      GO TO 1000                                                        INV3850
  360 DO 361 L=1,LX                                                     INV3860
      DO 361 I=1,LENGTH                                                 INV3870
      LYL=LY(L)                                                         INV3880
      DISCO=RTLOG(I)**LYL                                               INV3890
      VALIN(L,I)=VALIN(L,I)+( FCROP(L,I) /DISCO)                        INV3900
  361 CONTINUE                                                          INV3910
      WRITE(61,65) (NAME(I),I=1,19)                                     INV3920
      WRITE(61,60)                                                      INV3930
      DO 362 I=1,LENGTH                                                 INV3940
      RATE (I)=RATE (I)*100                                             INV3950
  362 CONTINUE                                                          INV3960
      WRITE(61,55)(LI(L),L=1,6)                                         INV3970
      WRITE(61,70)(LY(L),L=1,6)                                         INV3980
      DO 363 I=1,LENGTH                                                 INV3990
      WRITE(61,72) RATE(I),(VALIN(L,I),L=1,LX)                          INV4000
  363 CONTINUE                                                          INV4010
      GO TO 600                                                         INV4020
  400 CONTINUE                                                          INV4030
C                                                                       INV4040
C  CONTINUE WITH PROGRAM OPTION 3                                       INV4050
C                                                                       INV4060
      IF (IST.EQ.1)401,410                                              INV4070
  401 DO 402 L=1,LX                                                     INV4080
      DO 402 I=1,LENGTH                                                 INV4090
  402 FCROP(L,I)=VALIN(L,I)                                             INV4100
      VALIN(L,I)=0.0                                                    INV4110
      WRITE(61,65) (NAME(I),I=1,19)                                     INV4120
      WRITE(61,75)                                                      INV4130
      DO 403 I=1,LENGTH                                                 INV4140
  403 RATE(I)=RATE(I)*100.0                                             INV4150
      WRITE(61,55)(LI(L),L=1,6)                                         INV4160
      WRITE(61,70)(LY(L),L=1,6)                                         INV4170
      DO 404 I=1,LENGTH                                                 INV4180
      WRITE(61,72) RATE(I),(FCROP(L,I),L=1,LX)                          INV4190
  404 CONTINUE                                                          INV4200
      DO 405 I=1,LENGTH                                                 INV4210
      RATE(I)=RATE(I)/100.0                                             INV4220
  405 CONTINUE                                                          INV4230
      WRITE(61,76)                                                      INV4240
      GO TO 1000                                                        INV4250
  410 CONTINUE                                                          INV4260
      WRITE(61,65) (NAME(I),I=1,19)                                     INV4270
      WRITE(61,77)                                                      INV4280
      DO 411 I=1,LENGTH                                                 INV4290
  411 RATE(I)=RATE(I)*100.0                                             INV4300
      WRITE(61,55)(LI(L),L=1,6)                                         INV4310
      WRITE(61,70)(LY(L),L=1,6)                                         INV4320
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      DO 412 I=1,LENGTH                                                 INV4330
      WRITE(61,72) RATE(I),(VALIN(L,I),L=1,LX)                          INV4340
  412 CONTINUE                                                          INV4350
      WRITE(61,65) (NAME(I),I=1,19)                                     INV4360
      WRITE(61,78)                                                      INV4370
      DO 413 L=1,LX                                                     INV4380
      DO 413 I=1,LENGTH                                                 INV4390
  413 VALIN(L,I)=VALIN(L,I)-FCROP(L,I)                                  INV4400
      WRITE(61,55)(LI(L),L=1,6)                                         INV4410
      WRITE(61,70) (LY(L),L=1,6)                                        INV4420
      DO 415 I=1,LENGTH                                                 INV4430
      WRITE(61,72) RATE(I),(VALIN(L,I),L=1,LX)                          INV4440
  415 CONTINUE                                                          INV4450
      GO TO 600                                                         INV4460
  600 CONTINUE                                                          INV4470
      VALIN(L,I)=0.0  $FCROP(L,I)=0.0                                   INV4480
      WRITE(61,610)                                                     INV4490
C  READ CARD 12,END OF PROBLEM                                          INV4500
      READ(60,27)IEND                                                   INV4510
      IF(IEND-98)900,100,910                                            INV4520
  900 WRITE(61,99)                                                      INV4530
  910 STOP                                                              INV4540
      END                                                               INV4550
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3200 FORTRAN DIAGNOSTIC RESULTS - FOR INVEST6

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Project headquarters are also at:

Boise, Idaho
Bozeman, Montana (in cooperation with Montana State University)
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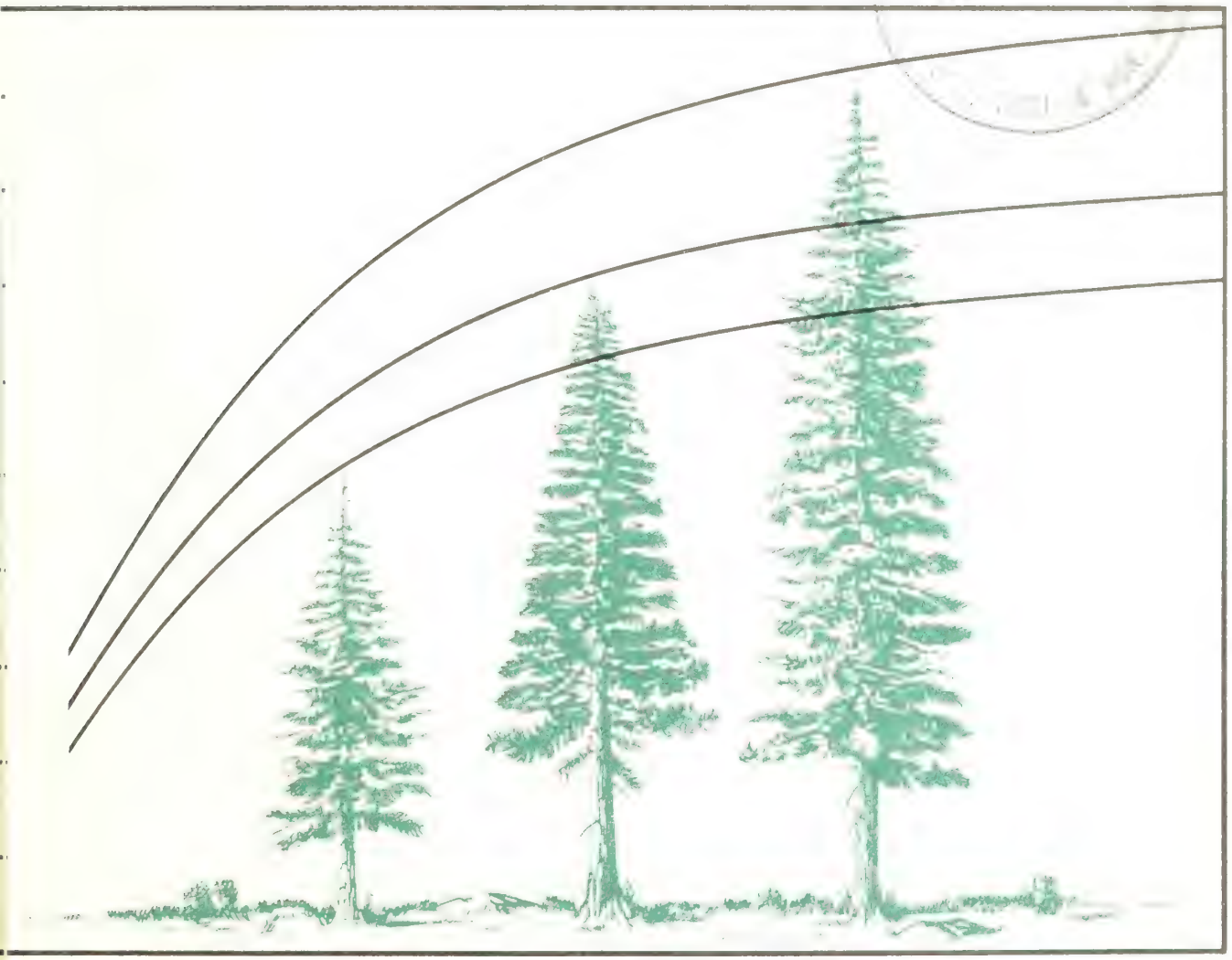
A METHOD FOR CONSTRUCTING SITE INDEX CURVES FROM MEASUREMENTS OF TREE AGE AND HEIGHT- ITS APPLICATION TO INLAND DOUGLAS-FIR

by JAMES E. BRICKELL



U.S. Forest Service Research Paper INT-47, 1968
Intermountain Forest and Range Experiment Station
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U.S. Forest Service
Research Paper INT-47
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FOREWORD

This paper describes a method of constructing site index curves from one-time measurements of age and height of trees in the dominant stand. Site index curves for Engelmann spruce (Picea engelmannii Parry) have already been constructed using this method (1).[1] In this paper curves are constructed for inland Douglas-fir (Pseudotsuga menziesii var. glauca (Mirb.) Franco) to illustrate how to use the method.

This method has the advantage of being applicable to the kind of site tree data usually taken in the course of forest inventories. Moreover, the disadvantages of these data are compensated for to some degree by the fact that the resulting site index curves will usually be used with the same kind of data, containing the same hidden effects of past damage.

The method is a generalization of the Osborne-Schumacher method (10) which assumes equal representation of a particular site quality in all age classes. The generalization does not require residuals about the mean curve of height over age to be normally distributed. A disadvantage of the method proposed in this paper is that it requires a relatively large number of sample trees--at least 1,500 paired measurements of age and height should be available.

The site index curves for inland Douglas-fir resulting from using this method are recommended for use in the northern and central Rocky Mountain area. These curves are shown on a page inserted in the middle of the publication. This page is designed so it can be detached for use in the field. Table 3 on page 14 shows height of trees in the dominant stand for various combinations of age and site index. Equations by which site index can be estimated from age and height are given on pages 20 and 22. These equations are especially useful in adapting the system of site index curves to use in electronic computer programs.

[1] Numbers in parentheses refer to Literature Cited.

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A METHOD FOR CONSTRUCTING SITE INDEX CURVES FROM MEASUREMENTS OF TREE AGE AND HEIGHT--ITS APPLICATION TO INLAND DOUGLAS-FIR

INTRODUCTION

For many years the most widely followed practice in describing forest site quality has been the use of a quantitative measuring system--site index curves. These must be developed for individual species and are supposed to represent the relationship between height and age of the average dominant and codominant trees on the site. These curves can be derived from measurements that indicate height and age of selected trees at different periods in time, or from measurements of height and age at one point in time on a large number of trees that range in age from young to old.

The first method, which uses either stem analysis data or recurrent measurements of selected trees on permanent sample plots, has usually been followed in recent years when site index curves or growth and yield information are the objectives of the study and data are collected for that purpose. Trees are selected for stem analysis or recurrent measurements so as to exclude those that have been subjected to height-growth-inhibiting injuries. Reliable use of curves derived from this kind of data presupposes that trees measured for comparison with the curves also have been free of injuries throughout their lives. When selecting trees to compare with the curves in the course of normal fieldwork it is seldom practical or even possible to limit a sample to the kind of uninjured trees on which the curves were based. Too often a tree may have sustained some injury in the past that cannot be detected by an observer on the ground. As a result, some trees that have suffered height-growth-inhibiting injuries are generally included in samples. Such sample trees will give an underestimate of site quality when compared with site index curves based on uninjured trees.

This is not intended as a criticism of the use of stem analysis or recurrent measurement data for site index curve development when such data are obtained with probability sampling techniques. On the other hand, when one is forced to use one-time measurements of tree height and age, such as may be collected in forest inventories, there is reason to think that both the trees on which the curves are based and those measured subsequently to estimate site index are from similar populations; that is, populations of trees as they exist in the forest. Thus, the curves are developed from the same kind of measurements as those with which they will be used, which may tend to reduce any bias arising from an observer's inability to detect the effects of previous top damage.

The site index curves currently being used for many species in the Western United States are based on paired measurements of age and height taken on trees in the dominant stand at one point in time. Such data are more easily collected in the course of forest inventories and are, for some species, the only data presently available. This is likely to be true, to an extent, for some time in the future. It is the purpose of this paper to show how this kind of data can be used to construct site index curves which are free of bias that could be introduced by the assumptions implicit in older methods.

METHODS FOR CONSTRUCTING CURVES

The methods of constructing site index curves as described in the forestry literature will result in either anamorphic (proportional) curves, or polymorphic (nonproportional) curves. Polymorphic curves vary in shape from one site to another. If their shape is well determined, they are generally considered more consistent with the known growth habits of trees. Therefore, polymorphic curves are to be preferred for estimating site index (6, 12, 2).

The Osborne-Schumacher method results in polymorphic curves based on the standard deviation of residuals about the mean curve of height over age. Fractions and multiples of the standard deviation are used in the construction of the actual curves at various site index levels. The assumption on which this method is based was stated by Osborne and Schumacher as follows:

> A necessary condition for the correct determination of site index is that it be intrinsically independent of plot age; for then the proportion of the sample plots whose site indexes are better--or poorer--than any given site index is the same, in the long run, at one age as at another; and, conversely, site index may be identified by associating it with the probability of occurrence. For example, the site qualities that are the most productive 10 percent of the area in a timber type should be represented by 10 percent of the sample plots in each age class whose height of average dominant--or dominant and codominant tree is greatest.

The procedure for site index curve construction given in this paper rests on the validity of the Osborne-Schumacher assumption, which can be related to site index curves as follows: If all land of a given site quality within a forest region is represented by areas of land in all age classes proportional to that part of the total land area in that particular site quality,[2] then the average height growth curve of trees in the dominant stand on land of that site quality can be represented by a curve that is above or below the mean curve of height on age by a distance which represents the same probability level in the distribution of residuals at all ages. This distance will, of course, vary with age.

In certain cases patterns of land use in the past may render this assumption invalid. Curtis (3) found this to be so with some tree species in New England. In this study it has been assumed that previous land use patterns have not operated to produce such an effect for the following reasons:

1. The data were drawn from a wide geographic area embracing several different economic regions

2. Most of the data came from National Forests where cutting practices have been rather different from those on smaller private holdings and

3. The effects of cutting practices and land use, if any, have been felt for at least 2 centuries less time in the Mountain States than in New England.

In the absence of evidence to the contrary, it is implicitly assumed that there is no relation between site and the incidence of fire, windfall, and insect damage.

PRELIMINARY ANALYSIS OF DATA

Unfortunately, only total age was recorded for the trees measured in this study, although age at breast height is a more reliable age upon which to base site index curves (9, 13, 5). Before a tree reaches this height, competition from brush, weeds, grass, etc., is likely to influence height growth to such an extent that any effect which the site itself may have on height growth is entirely obscured.

---

[2] That is, the expected value of

$$a_{ij} / \sum^{j} a_{ij} = \sum^{i} a_{ij} / \sum\sum^{ij} a_{ij} ,$$

where a_{ij} denotes the land area in the i^{th} age class and the j^{th} site class. $\sum^{j} a_{ij}$ is all land bearing stands in the i^{th} age class. $\sum^{i} a_{ij}$ is all land in the j^{th} site class, and $\sum\sum^{ij} a_{ij}$ is total land area for the species in the forest region being considered.

More than 3,000 Douglas-fir trees were measured for total height as well as total age. All were located on forest inventory plots in the northern and central Rocky Mountains (fig. 1). From one to three trees were measured at each location and each tree was counted as a separate observation. To qualify for sampling, trees had to be in the dominant portion of the stand and appear to have been free of injury and suppression throughout their lives.

The overall area shown in figure 1 was divided into five subregions, differing in respect to general climatic conditions that might influence tree growth (14). Each site tree observation was tagged by a subregion code of 1 through 5. This allowed later segregation of the site index predictions so as to test the shape of the final system of curves within each of the five subregions

Trees 200 years of age and older were rejected in constructing the curves, leaving 3,183 trees in the sample. Trees 200 years of age or older are likely to be so large in diameter that increment borers ordinarily available would not reach to the pith; therefore, an accurate estimate of age would not be obtained. Also, top damage that the tree may have sustained in the past is often difficult to detect in an old tree.

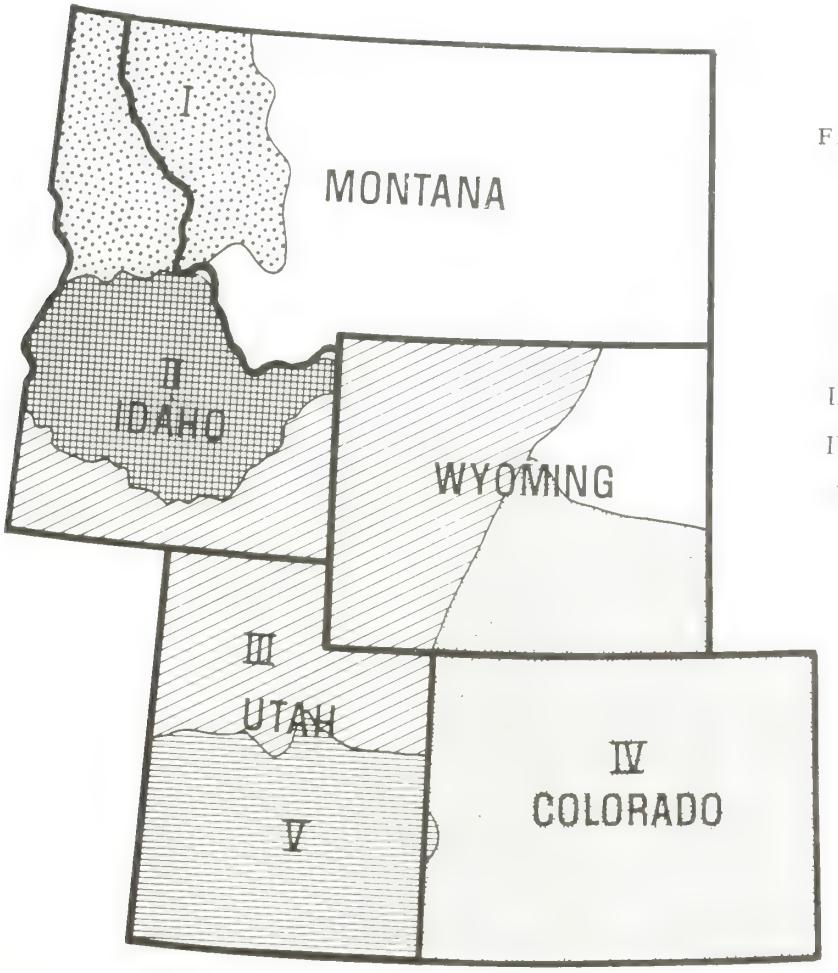

Figure 1.--The area from which the data used in this study were drawn. Subregions are:

I
II
III
IV
V

The trees left in the sample were sorted into 20-year-age groups and the distribution of heights within age groups was plotted. It was apparent that the distributions of heights within most of the 20-year-age groups were skewed, possibly due to the spread of ages within classes, and the intraclass correlation of height with age. It seemed likely, in any case, that the distribution of residuals about the mean curve of height over age would be nonnormal. If so, then the Osborne-Schumacher method could not be used unless skewness and kurtosis were the same at all ages. Otherwise, one standard deviation above the mean curve would reflect a different level of probability at different points along the curve, and any resulting site curves would be inconsistent with the basic assumption as stated on page 2.

DERIVATION OF CURVES

The method used in estimating the curves presented in this paper follows five distinct steps:

1. Sorting the site tree observations according to ascending values of total tree age and dividing the sample into agewise segments, each segment containing about 100 trees.

2. Fitting an average curve of total height over total age to the mean age and mean height of sample segments.

3. Locating a series of probability percentage points in the distribution of residuals around the average curve within each segment of the sample.

4. Fitting a series of curves of the same algebraic form to all points located at the same probability level in the several sample segments. Each curve is then associated with a particular level of probability of occurrence.

5. Harmonizing the series of curves obtained in step 4 above by expressing the coefficients of the curve equations as functions of site index. This results in one equation for the system of site index curves.

SORTING SITE TREE OBSERVATIONS

Because of the evident skewness of the distributions of heights within 20-year-age classes, the site tree observations were separated into groups, or sample segments, according to ascending values of total tree age. These sample segments were established so as to include 100 observations each, as nearly as was possible without breaking up groups of trees of the same age. Statistical tests for significance of kurtosis require samples of this size if sufficient sensitivity is to be attained.

A total of 29 classes was thus obtained, each class representing a varying age span--most of these fell within the range of 4 to 7 years. The number of trees in each sample segment, mean age, mean height, and standard deviation of the residuals around the average curve of height over age are shown in table 1.

Table 1.--Agewise segmenting of site tree observations for the purpose of residual distribution analysis

Sample segment	Age span	No. of trees	Mean age	Mean height	$S_{\cdot}$
	Years		Years	Feet	
1	0-35	99	28.4	30.1	14.5
2	36-43	105	40.1	41.4	13.5
3	44-48	98	46.1	43.5	13.6
4	49-53	107	50.9	50.4	16.0
5	54-58	116	56.1	54.4	17.5
6	59-62	117	60.3	57.1	16.1
7	63-66	118	64.6	60.2	17.2
8	67-70	134	68.7	61.3	18.7
9	71-74	108	72.3	59.9	18.8
10	75-78	105	76.4	61.2	19.9
11	79-82	116	80.5	63.2	19.8
12	83-86	99	84.6	61.5	17.5
13	87-91	108	89.3	65.2	21.4
14	92-96	106	94.1	66.4	18.9
15	97-101	107	99.1	72.3	20.4
16	102-107	108	104.8	65.5	19.5
17	108-112	102	110.0	72.0	18.7
18	113-118	105	115.5	71.6	20.6
19	119-122	101	120.3	71.2	19.7
20	123-128	105	125.5	73.2	21.3
21	129-134	111	131.3	75.6	21.0
22	135-140	137	137.7	76.6	22.8
23	141-147	109	144.3	70.9	20.3
24	148-153	106	150.4	78.3	22.5
25	154-160	107	157.9	71.2	21.4
26	161-168	103	164.7	75.9	22.0
27	169-175	104	172.6	74.8	20.1
28	176-184	103	180.1	76.0	24.2
29	185-199	139	190.8	76.2	21.8

[1] Standard deviation of height residuals around the mean curve of height over age.

FITTING AVERAGE HEIGHT-AGE CURVE

To estimate the mean curve of height on age, a growth function of suitable form was fitted to the sample segment means of age and height, and properly weighted according to the number of trees in each segment. Several growth equations were fitted to the data and evaluated in an attempt to express the average relationship between tree height and tree age. The most appropriate was found to be:

$$H = a\,[1 - b \cdot \exp(-kA)]^{1/1-m}$$

where:

H = total tree height

A = total tree age

a, b, k, m are coefficients of the equation to be estimated by the method of least squares.

exp(-kA) means e, the base of Naperian logarithms, taken to the (-kA) power.

This model and its use as a growth curve have been discussed in detail by Richards (12). It can be seen that the function is not linear in its parameters, nor can it be made so by transformation. To fit this equation, it is necessary to use iterative numerical methods that, in this case, were those embodied in a computer program produced by the Esso Research and Engineering Corporation. The least squares criterion was satisfied by the following values of the coefficients:

a = 76.0

b = 1.0

k = 0.0290833

m = 0.398601

The estimates of the first two coefficients that were used to start the iterative fitting process remain unchanged. After the second two coefficients were estimated, any reduction in the error sum of squares obtained by changing coefficients a and b was insignificant because the initial estimates were so close to the optimum least squares solution. This average height over age curve and the points to which it was fitted are shown in figure 2.

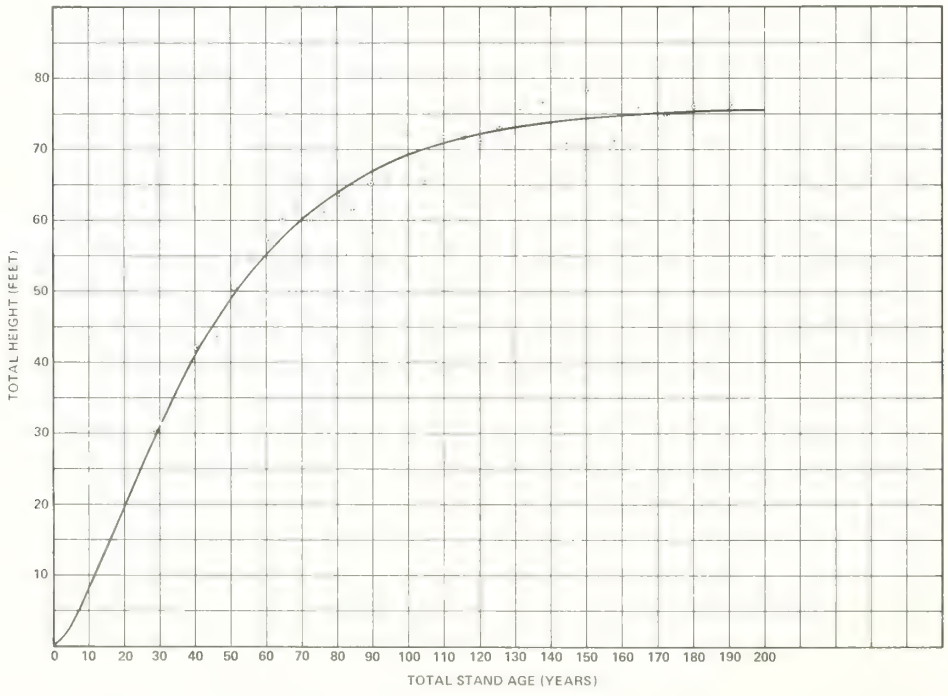

Figure 2.--The average curve of height over age for inland Douglas-fir. The plotted points are (mean age-mean height) coordinates for each sample segment.

LOCATING PROBABILITY PERCENTAGE POINTS

After a prediction equation for average height was obtained, a height was predicted for each tree in the sample. This predicted height was subtracted from the tree's actual height, and the residuals obtained thereby were accumulated separately for each of the 29 sample segments. The 100 or so residuals in each sample segment, then, formed a frequency distribution. These distributions were nonnormal in most cases.

For each within-segment distribution of residuals the standard deviation (S) was calculated. Estimates of the moment ratios β_1 and β_2 were computed as indices of skewness and kurtosis according to the method of k-statistics given by Kendall and Stuart (8) where the k-statistics are sample estimates of the distribution cumulants. The moment ratios were computed from the corresponding cumulant ratios.

Figures 3 and 4 show the coefficients β_1 and β_2, respectively, plotted over corresponding sample segment mean age. It will be noted that nearly two-thirds of the segment distributions are significantly skewed, while only six depart significantly from the mesokurtic condition, three being platykurtic and three leptokurtic. Considering both measures of nonnormality, only eight of the 29 distributions within sample segments can be called normal distributions.

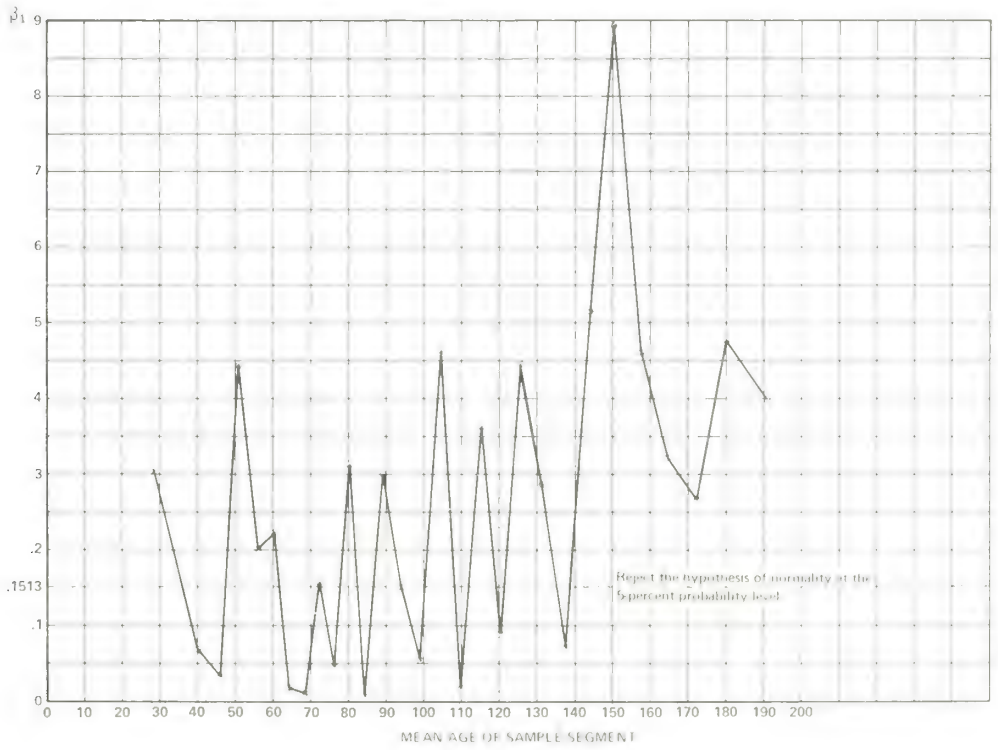

Figure 3.--Estimates of the β_1 coefficient plotted over corresponding sample segment mean age.

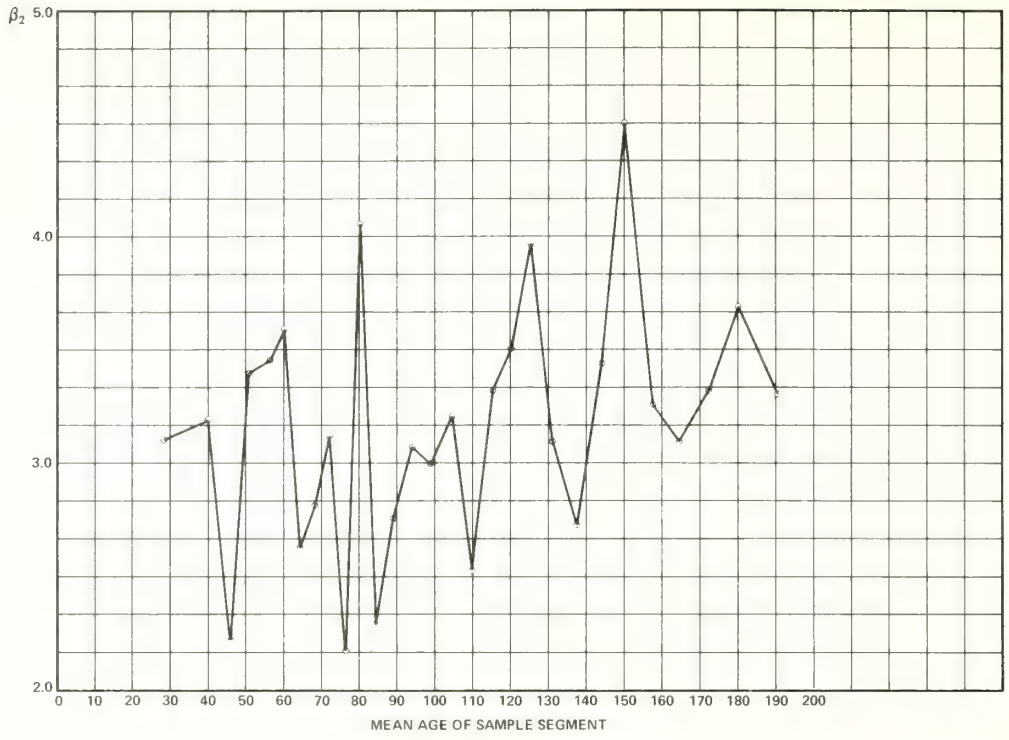

Figure 4.--Estimates of the β_2 coefficient plotted over corresponding sample segment mean age.

Definite trends of both β_1 and β_2 with age can be seen in figures 3 and 4. Because of these trends, the probability attached to a point one standard deviation from the mean in each distribution will vary with age. Consequently, the Osborne-Schumacher method could not be used without modification. In a series of skewed distributions such as this, the mean will not be located at the same point of probability in each distribution. The median, however, is by definition the 50-percent probability point in any distribution; if the distribution is symmetrical, the mean and the median coincide. Because the distributions of residuals in this case are not symmetrical, the mean curve of height on age does not represent points of equal probability at all ages.

Therefore, under the previously mentioned assumptions of equal representation of site quality in all age classes, the mean curve does not represent a true height growth curve. Rather, a curve fitted to the medians, or 50-percent probability points, of the within-segment distributions should describe a true height growth curve at that particular level of site index. Further, this curve would divide the population of forest sites into two parts, half being of poorer site quality, and half being better.

Figure 5 shows a skewed frequency distribution typical of the distributions of residuals within sample segments. The points marked .01, .05, .10, .25, .75, .90, etc., show the points in the distribution below which 1 percent, 5 percent, 75 percent, etc., of the forest sites in the population are expected to fall. All of the distributions of residuals in the 29 sample segments could be adequately described by Pearson's system of frequency curves (4). All except one of the distributions are of Type I or Type IV (fig. 6).

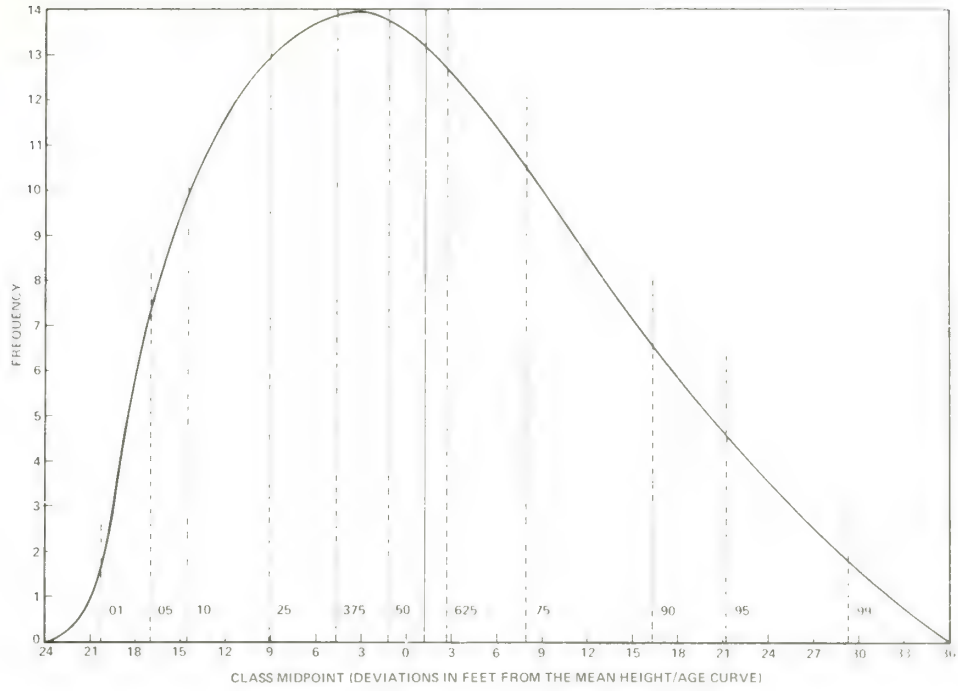

Figure 5.--A skewed frequency distribution typical of the distribution of residuals within sample segments.

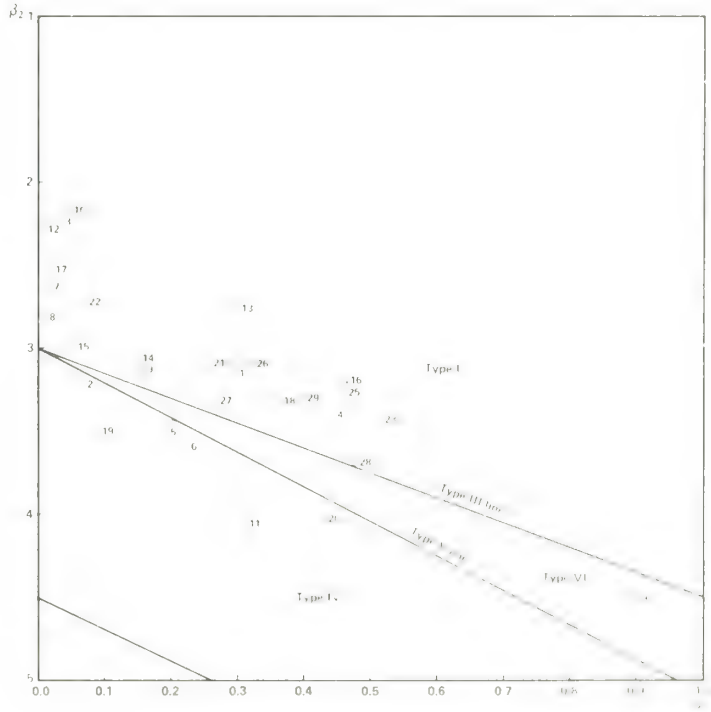

Figure 6.--Showing the types, according to Pearson's system, of the 29 within-segment distributions of residuals. Number beside each plotted point identifies the sample segment from which it came.

Nine percentage points of the distribution of heights within each age group were estimated using the tables of probability percentage points for Pearson's frequency distributions (7). These points represent the heights such that 1, 5, 10, 25, 50, 75, 90, 95, and 99 percent of the trees in each sample segment were shorter than the particular limit. The relative locations of these percentage points are shown in figure 5.

Heights at the several different probability levels were computed in the following manner for each sample segment:

1. For a given probability level, the distance from the mean in standard units[3] was found from the probability tables (7). Call this distance α.

2. Multiply α by S, which is the standard deviation of residuals within the sample segments.

3. A height corresponding to the mean age of the sample segment was predicted using the equation for the mean height over age curve (fig. 3). Call this predicted mean height $\hat{\bar{H}}$.

4. Call the mean residual of the within-segment distribution Δ.[4]

5. Then the height associated with this particular probability level (p) in the i^{th} sample segment is:

$$H_{ip} = \hat{\bar{H}} + \Delta + \alpha \cdot S .$$

In addition to the nine heights determined in this way, heights were obtained for the 37.5 and the 62.5 probability percentage points from the third and fifth octiles of the residual frequency distribution within each sample segment. This means of estimation is somewhat less precise than the procedure followed for the other nine height estimates. Nevertheless, it is unbiased.

FITTING CURVES TO EACH SERIES OF PROBABILITY PERCENTAGE POINTS

For all sample segments, the heights associated with a particular probability level were plotted over segment mean age. The curve drawn through the plotted points was either above or below the median curve, depending upon its probability level. It was not necessarily proportional to the average curve; in fact it was not proportional for any of the 11 probability levels. Yet no mathematical artifacts prohibited proportionality if the data had so indicated. Curves derived in this manner for the 10-, 50-, and 90-percent probability levels are shown in figure 7. To avoid confusion, curves for the other probability levels are not shown, but their appearance is quite similar. Nevertheless, the 11 curves differ in shape enough to indicate polymorphism that should be preserved in the final system of curves.

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[3] This means that the distribution's standard deviation is 1.0. Thus, a distance from the average of 1.5 or 2.3 means 1.5 or 2.3 times as far from the average as the standard deviation.

[4] Recall that the mean curve of height on age was fitted to the entire distribution of tree ages and heights. Therefore, there is no reason to expect that the mean residual within a sample segment will be zero.

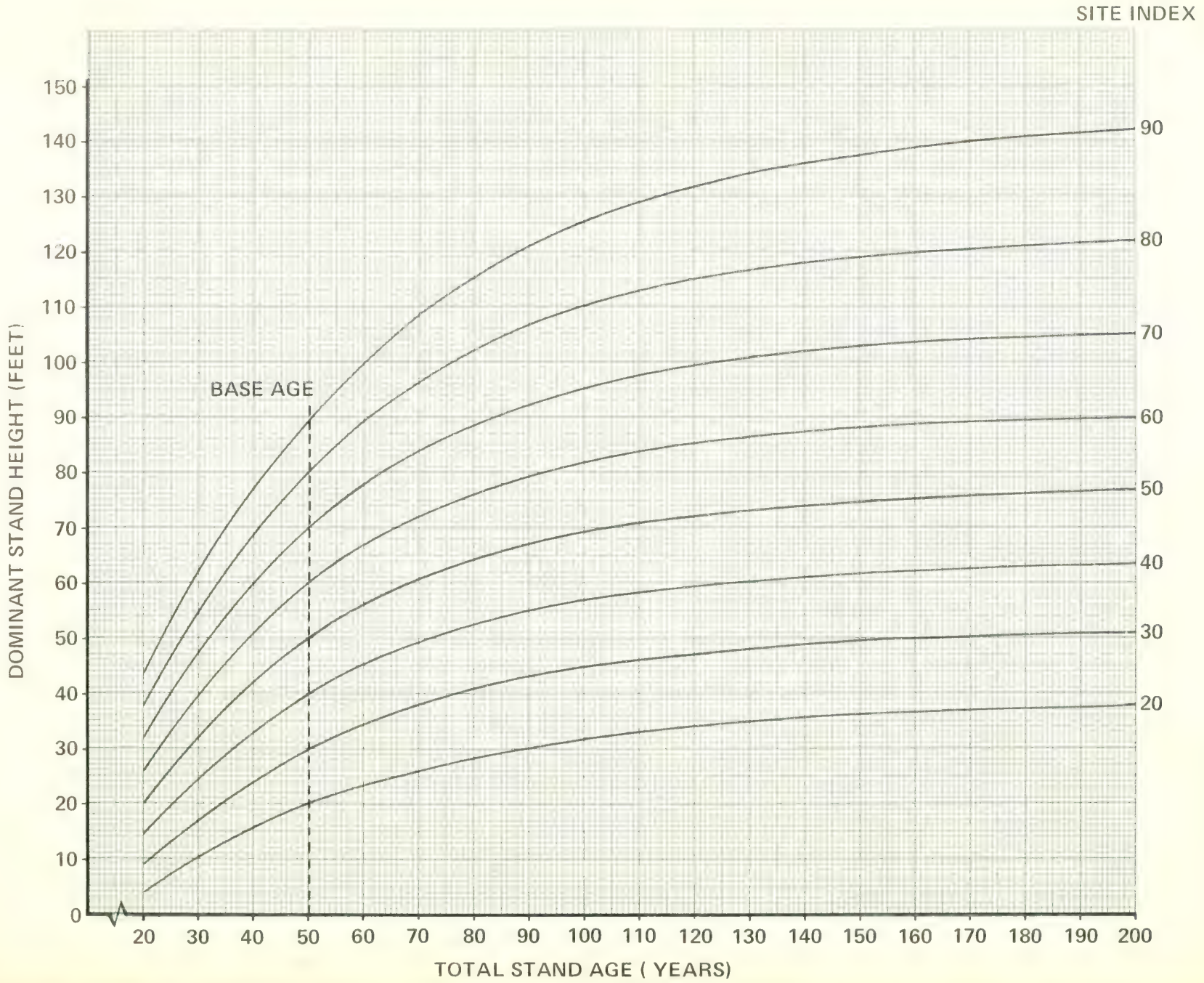
SITE INDEX CURVES FOR INLAND DOUGLAS-FIR IN THE NORTHERN AND CENTRAL ROCKY MOUNTAINS

HOW TO USE SITE INDEX CURVES

1. To estimate the average site index for a stand of inland Douglas-fir, measure total age and total height of trees that are in the dominant portion of the stand. Site trees should appear to have been in the dominant stand throughout their lives without having suffered top damage that inhibited height growth. The number of sample trees necessary to give any stated precision of estimate will depend on the variance in site index between trees in the stand. This is influenced by the size of the stand and the degree of its heterogeneity in site quality.

2. Using the curves on the other side of this sheet, or figure 11 or table 3 in Research Paper INT-47 from which this sheet was taken, estimate a site index value for each sample tree. (For computer applications, either of the equations on pages 20-22 of INT-47 can be used.)

3. The average site index for all sample trees will be the best estimate of average site index for the area sampled if selection of site trees was random with respect to site quality.


SITE INDEX
DOMINANT STAND HEIGHT (FEET)
BASE AGE
TOTAL STAND AGE (YEARS)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
20
30
40
50
60
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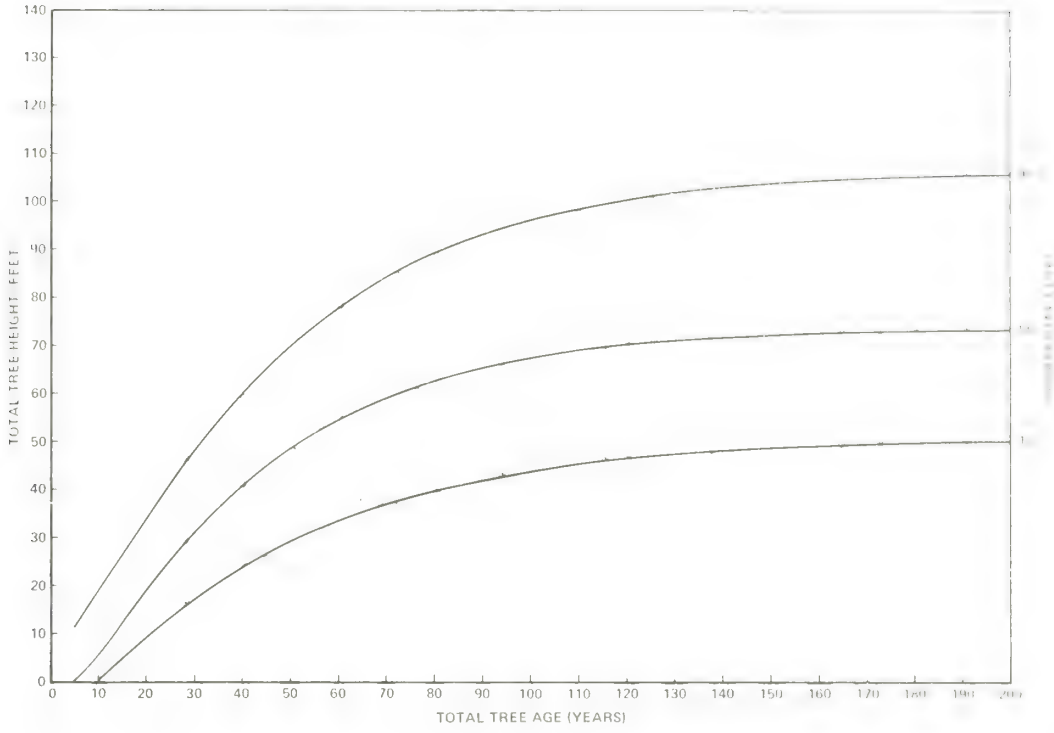


Figure 7.--Curves of height over age for the 10, 50, and 90 percentage of probability levels.

The growth function that was used for the mean height-age curve was fitted to each of the 11 equal-probability level curves. The estimates of the coefficients a, b, k, and m obtained for these curves are shown in table 2, where the different curve levels are identified by the percentage of trees expected to have a lower site index. Note that the value of the coefficient m remained at the value used to start the iterative fitting process in several cases. Evidently, this coefficient is quite poorly determined when there is as much variation around the curve as there was in these cases, and no observations exist in the neighborhood of the curve's inflection point. According to Richards (11), it is the m coefficient that determines the inflection point of the sigmoid curve described by this growth function.

Using the coefficients given, each curve was solved for height at an age of 50 years. This assigned a site index to each curve and to the set of points to which the curve was fitted. The root mean square residual of the points derived from probability percentages for each of the 11 curves follows:

Percent	Feet
0.01	2.48151
.05	1.97699
.10	2.10783
.25	2.41299
.375	2.68735
.50	2.39172
.625	2.97846
.75	2.49292
.90	2.91963
.95	3.42081
.99	5.86715

Table 2.--Coefficients and estimated site index of eleven polymorphic height over age curves

Probability level (percent)	Coefficients a	b	k	m	Site index (feet)
0.01	39.0055	0.940887	0.0194496	0.436483	17.87440
.05	45.5291	1.30145	.0229012	.1	25.13584
.10	50.6858	1.24789	.0230806	.1	29.07733
.25	60.3456	1.07016	.0270850	.308415	37.81088
.375	67.1239	1.0	.0290830	.398600	43.19466
.50	73.9369	1.16358	.0278033	.191505	48.42383
.625	80.9312	1.04128	.0308835	.398600	53.27936
.75	89.6517	.934803	.0290830	.398600	59.51743
.90	106.2990	.848792	.0267493	.398600	69.90275
.95	117.9460	.967460	.0232968	.175890	76.26919
.99	139.7280	.770341	.0209054	.323633	87.53819

HARMONIZING THE SYSTEM OF SITE INDEX CURVES

For each of the four growth function coefficients, the 11 different values shown in table 2 were plotted over the corresponding site index assigned to that curve, resulting in the scatter diagrams shown in figure 8. Apparently there was no trend of the coefficient m with site index. Coefficients a, b, and k, however, showed correlation with site index. The expressions best relating the coefficients to site index seemed to be:

$$f_1(S) = a = p_0 + p_1 S + p_2 S^2 \quad (2)$$

$$f_2(S) = b = q_0 + q_1 S \quad (3)$$

$$f_3(S) = k = \exp(r_0 + r_1 S + r_2 S^2) \text{ where} \quad (4)$$

S = site index.

Then, assigning a site index to each set of points bearing the same probability level, the function

$$H = f_1(S) \cdot \left\{1 - f_2(S) \cdot \exp\left[f_3(S) \cdot A\right]\right\}^{1/1-m}$$

was fitted to all 319 of the points from which the series of 11 curves had been derived. The fitting was done by the same iterative numerical process as was used for the less complex function. Each of the 319 points was assigned a weight proportional to the number of sample trees in the sample segment in which the point was located and inversely proportional to the residual sum of squares about the curve to which the point belonged. That is:

$W_{ij} \propto N_i / \Sigma res^2_j$, where

W_{ij} = the weight of the point located at the j^{th} probability level in the i^{th} sample segment.

N_i = the number of site tree observations in the i^{th} sample segment.

Σres^2_j = the sum of squared residuals about the curve at the j^{th} probability level.

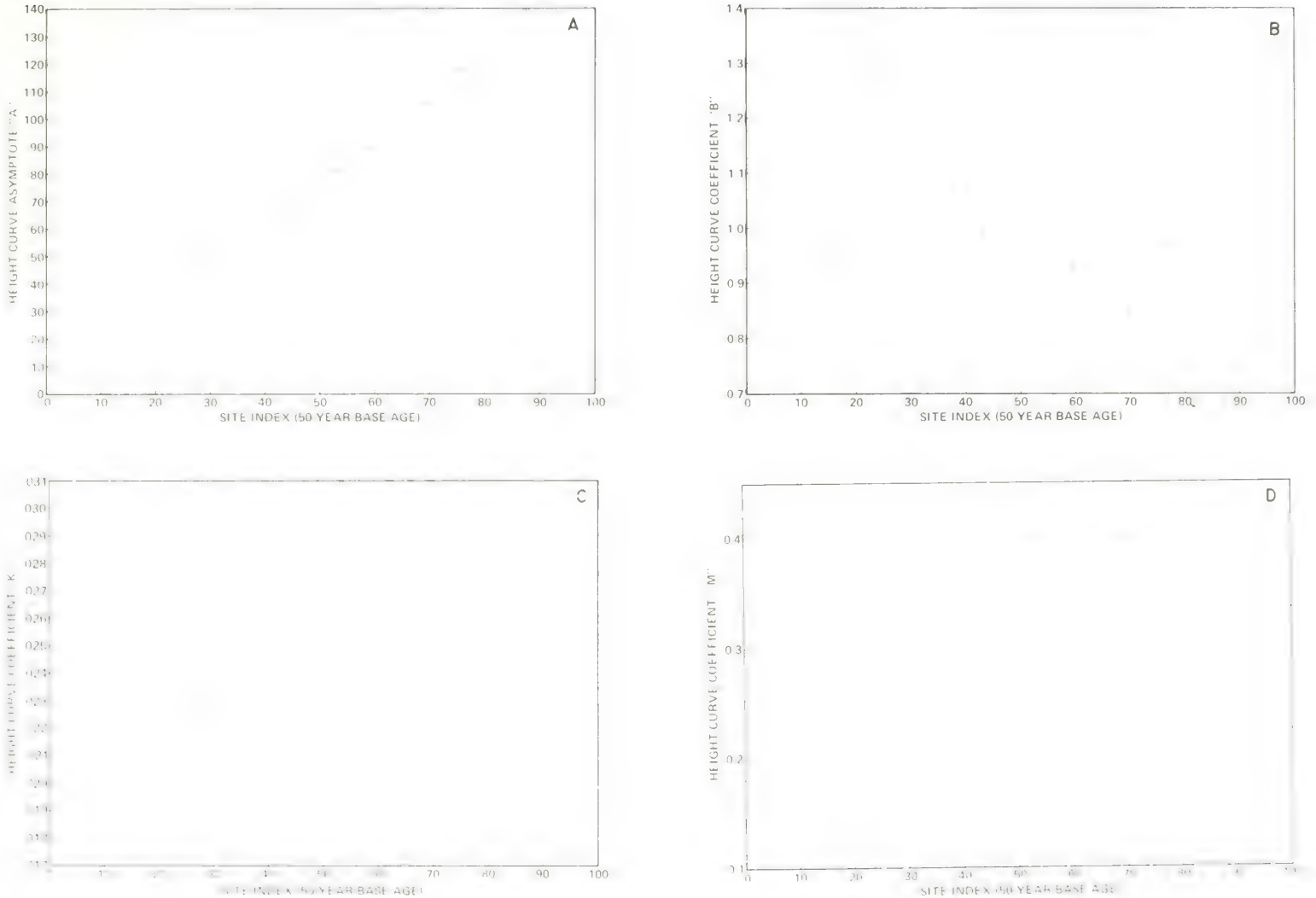


Figure 8. --A, The growth curve "a" coefficient plotted over site index; B, the growth curve "b" coefficient plotted over site index; C, the growth curve "k" coefficient plotted over site index; D, the growth curve "m" coefficient plotted over site index.

The equation finally obtained that expressed tree height as a function of age and site index is:

$$H = a\,[1-b\cdot\exp(-kA)]^{1/1-m}, \text{ where} \quad (5)$$

$$a = 20.618 + 0.864711\cdot S + 0.00529738\cdot S^2 \quad (6)$$

$$b = 1.40694 - 0.0042396\cdot S \quad (7)$$

$$k = \exp(-4.14672 + 0.017648\cdot S - 0.000161345\cdot S^2) \quad (8)$$

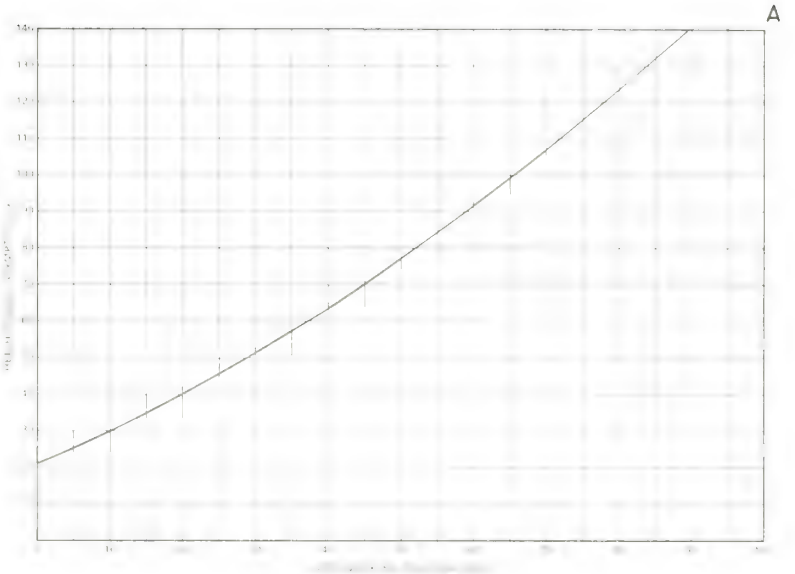
$$m = .05730421$$

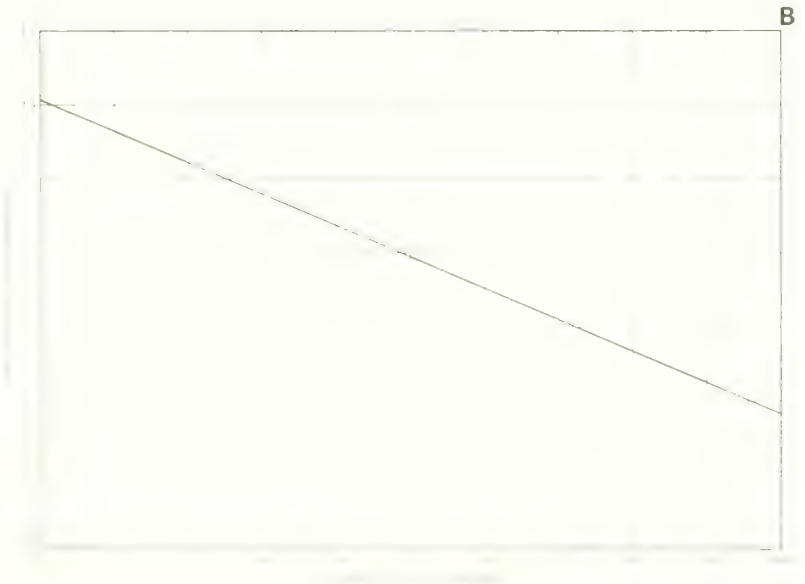
The relationships between coefficients a, b, and k, and site index, as they exist in the final equation, are shown in figure 9. The coefficient m remains the same for all levels of site index. Curves generated by this equation are shown on the heavy tearout sheet at the center of this paper. These are the completed site index curves. Table 3 gives height as estimated from these curves according to total tree age and site index.

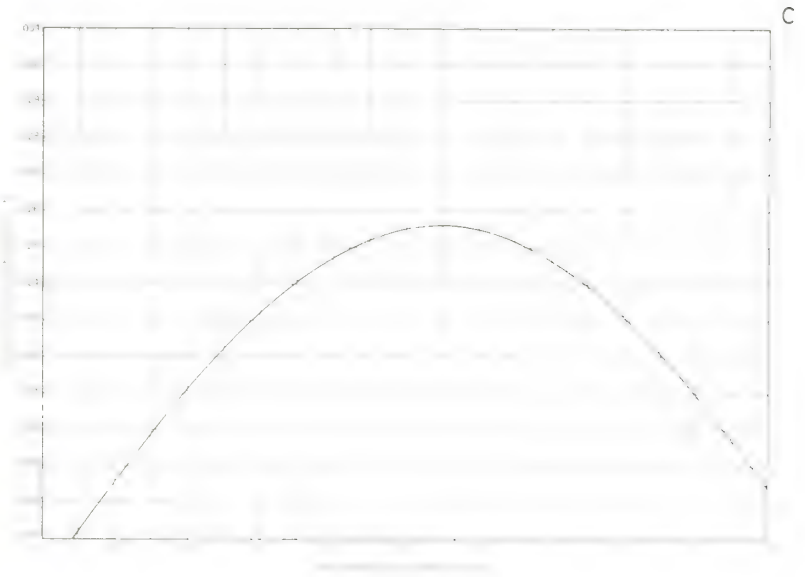
Table 3.--Height of trees in the dominant stand by age and site index

Total age (years)	Site index							
	20	30	40	50	60	70	80	90
	Feet							
20	4	9	14	20	26	32	38	44
30	11	18	25	32	40	48	55	62
40	16	24	33	42	51	60	69	78
50	20	30	40	50	60	70	80	90
60	23	34	45	56	67	78	89	100
70	26	38	49	61	72	84	96	108
80	29	41	53	64	76	89	102	115
90	30	43	55	67	79	92	106	121
100	32	45	57	69	82	95	110	125
110	33	46	59	71	84	98	113	129
120	34	47	60	72	85	99	115	132
130	35	48	61	73	87	101	117	134
140	36	49	61	74	87	102	118	136
150	36	49	62	75	88	103	119	138
160	37	50	62	75	89	103	120	139
170	37	50	63	76	89	104	121	140
180	37	51	63	76	89	104	121	141
190	37	51	63	76	90	105	122	141
200	38	51	63	76	90	105	122	142

Figure 9.--A, The final relationship between the growth curve "a" coefficient and site index; B, the final relationship between the growth curve "b" coefficient and site index; C, the final relationship between the growth curve "k" coefficient and site index.







TESTING CURVES FOR INDEPENDENCE OF AGE AND SITE INDEX

Lacking additional data, only a test of consistency between subregions was possible. To do this, a site index based on the newly developed curves was assigned to each tree in the sample. Then the trees were separated into five groups according to the geographic subregion from which they were drawn.

TESTING WITHIN EACH SUBREGION

Within each areal group and within all groups combined, an attempt was made to find significant trends of estimated site index with tree age by fitting the equation:

$$S = b_0 + b_1A + b_2A^2 + b_3A^3 \qquad (9)$$

to the joint distribution of tree age (A) and estimated site index (S). The multiple correlation coefficients thus obtained for data from subregions I, III, IV, and V failed to indicate significant difference from zero at the 95-percent probability level. Therefore, the hypothesis that there is correlation between tree age and estimated site index was rejected for these subregions, and the two were assumed independent.

In the data from subregion II, however, it appeared that correlation between age and estimated site index did exist. The source of this correlation was further traced to the data from six National Forests in central Idaho. This implied that height-growth curves of inland Douglas-fir have the same shape for a given level of site index throughout the northern and central Rocky Mountains except in a relatively small area of central Idaho.

EFFECT OF OVERSTORY COMPETITION

Experience with Douglas-fir in central Idaho indicated that in at least part of the area this species is largely found in the understory.[5] Often it takes the form of a younger stand coming up beneath old-growth ponderosa pine. Competition from an overstory may have thus changed the shape of the typical growth curve somewhat.

Supporting this possibility was the fact that the correlation between age and estimated site index was present to the greatest extent in trees less than 70 years old. On the average, these trees were not as tall for their age as was expected. Competition may have reduced the height growth of young trees in some areas but, if so, then the reduction in diameter growth should have been even greater. It is common knowledge that diameter growth is more sensitive to competition than height growth. This made possible a statistical test to determine whether or not competition was more severe for young trees in the six National Forests studied than it was for young Douglas-fir trees throughout the rest of the northern Rocky Mountain area.

For the test, all trees in the sample 70 years old or less were separated into two groups according to the area from which they were drawn. Trees from the areas where competition was thought to have inhibited height growth comprised one set of data, and trees from all other areas comprised the other. To each set of data was fitted the equation:

$\ln H = b_0 + b_1 \ln D$, where

$\ln H$ = Naperian logarithm of total tree height

$\ln D$ = Naperian logarithm of d.b.h.

b_0, b_1 = regression coefficients

[5] Communication from Charles A. Wellner, Assistant Director, Intermountain Forest and Range Experiment Station.

The results are shown in figure 10. The two regression lines are significantly different at the 95-percent confidence level. It can be seen that trees in central Idaho usually have a smaller d.b.h. for the same height. This indicates that trees measured as site trees were indeed subject to greater competition in parts of central Idaho than elsewhere. It does not mean that better site quality had produced more rapid height growth--hence better tree form--because these trees were shorter than expected. The site seems to be actually better than young trees would indicate.

If the foregoing can be accepted as the reason for lack of independence between age and estimated site index on six National Forests, then it can be assumed that, but for the pressure of overstory competition on these particular Forests, the height growth curves would be the same as they are elsewhere in the northern Rocky Mountains. This assumption was made, and the system of curves published here is recommended for use throughout the area.

The foregoing discussion might give rise to two questions: (a) what biasing influence could the inclusion of subregion II data have had on the system of site index curves so far as their use in other subregions is concerned? and (b) why were trees which had been affected by competition measured as site trees in the first place?

The answer to the first question is that although some biasing effect would seem inevitable, statistical tests failed to show that age and estimated site index were not independent. Therefore, any bias in the curves would be of little, if any, practical consequence. The second question can only be answered by pointing out that Forest Survey crews were obliged by field sampling rules to measure Douglas-fir site trees on or near the sample plot so long as the stand was predominantly Douglas-fir by basal area, even though the Douglas-fir may have been mostly in an understory position.

ESTIMATION EQUATIONS FOR USE IN COMPUTER PROGRAMS

The equation that expresses tree height as a function of age and site index cannot be readily solved for site index given age and height. The numerical procedure necessary to achieve a solution would probably not converge to a solution rapidly in many cases and would thus require an excessive amount of computer time. Table lookup procedures require the storage of a table in the computer memory core, which has definite disadvantages, including the necessity for interpolation between cells of the table. Interpolation in a nonlinear system can lead to inaccuracies.

For these reasons, it was decided to devise a means by which site index could be computed directly from age and height. To do this, a regression equation was developed that approximated the surface of site index over age and height. The surface was generated from the equation of height over age and site index (equation 5). Figure 11 shows site index plotted over height for several different age levels. At age 50, site index is identically equal to height, because 50 years is the index base age of the system of curves. It was found that equations of the form:

$$S = b_0 + b_1 H + b_2 H^2 + b_3 H^3 + b_4 H^5 \qquad (10)$$

gave the best fit for most ages, including age 50, where b_1 has to equal unity and all other coefficients are zero. Fitting this equation to the curves of site index over height for each

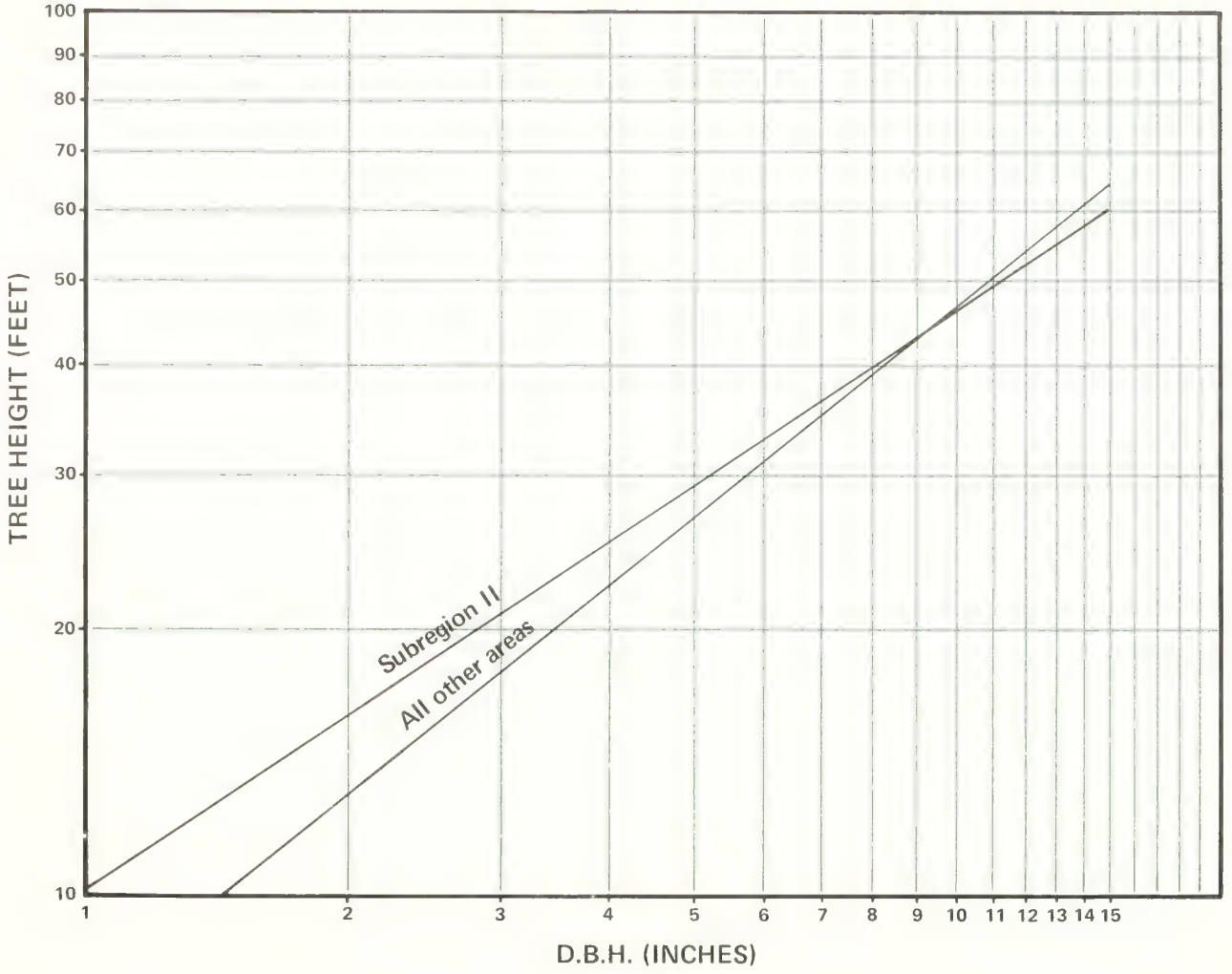


Figure 10.--Regressions of height on diameter for site trees less than 70 years old in subregion II, and in all other areas.

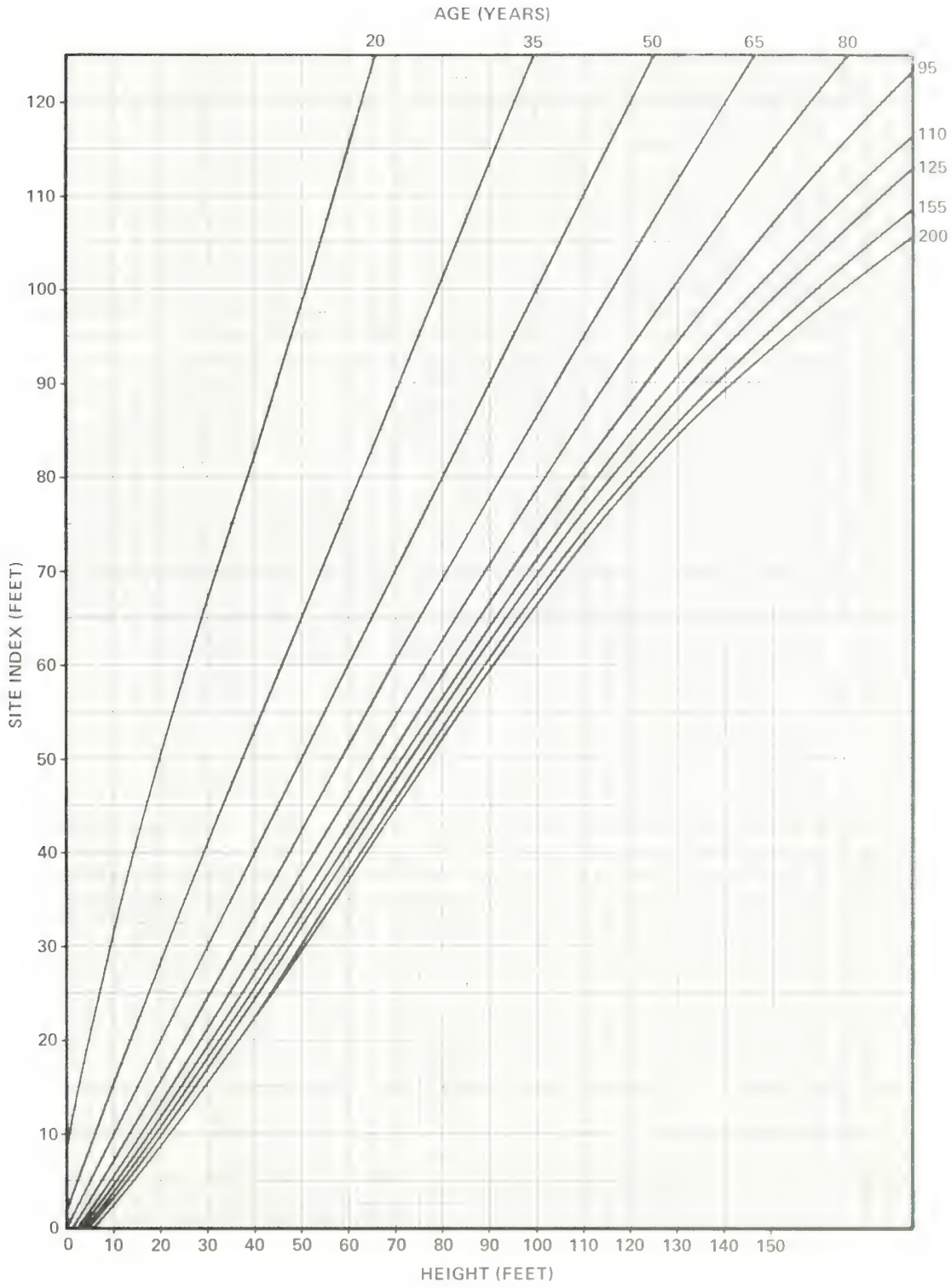


Figure 11.--The relationship between site index and height for several different ages.

age between 20 and 200, inclusive, resulted in 181 sets of coefficients. Plotted over age, these coefficients showed very definite trends, which could be described[6] by the equations:

$$\hat{b}_0 = c_1(A^{-\frac{1}{2}} - 50^{-\frac{1}{2}}) + c_2(A^{-2.5} - 50^{-2.5}) + c_3(A^{-3.5} - 50^{-3.5}) + c_4(A^{4} - 50^{4}) + c_5(A^{5} - 50^{5}) \quad (11)$$

$$\hat{b}_1 - 1 = k_1(A^{-1.5} - 50^{-1.5}) + k_2(A^{-4} - 50^{-4}) + k_3(A^{-5} - 50^{-5}) + k_4(A^{4} - 50^{4}) \quad (12)$$

$$\hat{b}_2 = p_1(A^{-2} - 50^{-2}) + p_2(A^{-5} - 50^{-5}) + p_3(A - 50) \quad (13)$$

$$\hat{b}_3 = q_1(A^{-1} - 50^{-1}) + q_2(A^{-5} - 50^{-5}) + q_3(A^{1.5} - 50^{1.5}) + q_4(A^{4} - 50^{4}) \quad (14)$$

$$\hat{b}_4 = r_1(A^{-\frac{1}{2}} - 50^{-\frac{1}{2}}) + r_2(A^{4.5} - 50^{4.5}) \quad (15)$$

If these equations are conditioned to pass through the origin as shown, the necessary coefficient values at age 50 are maintained. Substituting the equations for the b_i coefficients into equation (10) and adding tree height, an equation is obtained that expresses site index as a function of age and height. The final site index approximating equation is:

$$S = H + \sum_{i=1}^{18} b_i X_i, \text{ where} \quad (16)$$

S = site index in feet of total height at a total tree age of 50 years.

H = total height of a sample tree.

A = total age of a sample tree.

[6] Satisfactory expressions for the coefficients were derived from regression analysis. In fitting the necessary regressions, all variables that contained a negative integer power of age were scaled to avoid subtraction of two very small numbers. If a variable was A^{-k}, for example, it would have been input to regression as $[(10^{2k}A^{-k}) - 2^k]$. The subtraction of 2^k makes the value of the variable equal to zero at age 50. All variables in the equation were so treated as to equal zero at age 50; therefore at age 50--the index base age--site index equals height.

$b_1 = 0.40984664E+02$ [7]

$b_2 = 0.45211527E+04$

$b_3 = 0.12305938E+06$

$b_4 = -0.53328682E-08$

$b_5 = 0.37808033E-10$

$b_6 = 0.21664152E+03$

$b_7 = -0.15812149E+06$

$b_8 = 0.18940308E+07$

$b_9 = -0.10230592E-09$

$b_{10} = -0.60686119E+01$

$b_{11} = -0.25351090E+05$

$b_{12} = 0.33512858E-04$

$b_{13} = 0.17024711E-02$

$b_{14} = 0.39836720E+03$

$b_{15} = -0.88665409E-08$

$b_{16} = 0.40019102E-14$

$b_{17} = -0.46929245E-08$

$b_{18} = -0.16640659E-20$

$X_1 = (A^{1} - 50^{1})$

$X_2 = (A^{2.5} - 50^{2.5})$

$X_3 = (A^{1.5} - 50^{1.5})$

$X_4 = (A^{4} - 50^{4})$

$X_5 = (A^{5} - 50^{5})$

$X_6 = H(A^{-1.5} - 50^{-1.5})$

$X_7 = H(A^{-4} - 50^{-4})$

$X_8 = H(A^{-5} - 50^{-5})$

$X_9 = H(A^{4} - 50^{4})$

$X_{10} = H^2(A^{-2} - 50^{-2})$

$X_{11} = H^2(A^{-5} - 50^{-5})$

$X_{12} = H^2(A - 50)$

$X_{13} = H^3(A^{-1} - 50^{-1})$

$X_{14} = H^3(A^{-5} - 50^{-5})$

$X_{15} = H^3(A^{1.5} - 50^{1.5})$

$X_{16} = H^3(A^{4} - 50^{4})$

$X_{17} = H^5(A^{-1} - 50^{-1})$

$X_{18} = H^5(A^{4.5} - 50^{4.5})$

The standard error of estimate and coefficient of multiple determination for this expression are, respectively,

$S_{yx} = 0.238673$ foot of site index

$R^2 = 0.999936$

---

[7] Here the letter E followed by a sign and two digits means that the number preceding the E is to be multiplied by 10 raised to the power of the two digits. That is, nE+02 means n X 10^2; nE-01 means n X 10^{-1}, where n is the decimal fraction preceding the E.

If a shorter equation, with less precision, is desired, the following may be used:

$$S = H + \sum_{i=1}^{5} c_i Y_i, \text{ where} \qquad (17)$$

$c_1 = 0.10108708E+03$ $\quad Y_1 = (A^{-\frac{1}{2}} - 50^{-\frac{1}{2}})$

$c_2 = 0.12204763E+03$ $\quad Y_2 = H(A^{-1.5} - 50^{-1.5})$

$c_3 = 0.14082397E-12$ $\quad Y_3 = H(A^{5} - 50^{5})$

$c_4 = -0.13140717E+05$ $\quad Y_4 = H^2(A^{-5} - 50^{-5})$

$c_5 = 0.13492191E-04$ $\quad Y_5 = H^5(A^{-3} - 50^{-3})$

For this equation $S_{yx} = 0.904479$ and $R^2 = 0.999080$.

These equations are valid for ages from 20 to 200 years and for site indices from 10 to 110. The site index of trees older than 200 years should be estimated as if age were 200.

HOW TO USE THIS MATERIAL

To estimate the average site index for a stand of inland Douglas-fir, measure total age and total height of trees that are in the dominant portion of the stand. Site trees also should appear to have been in the dominant stand throughout their lives. The number of sample trees necessary to give any stated precision of estimate will depend on the variance in site index between trees in the stand. This is influenced by the size of the stand and its heterogeneity.

Estimate a site index value for each sample tree by using any one of the following:

1. The curves on the tearout page.

2. Figure 11 on page 19.

3. Table 3 on page 14.

4. Either equation 16 on page 20 or equation 17 on this page.

Compute the average of the site index estimates for each sample tree. This average will be the best estimate of site index for the area sampled.

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RECENT FOREST SURVEY PUBLICATIONS

Title	Number	Date
Timber Resources of Idaho	Forest Survey Release 3	1962
The Forest Resources of Western Montana	Resource Bulletin INT-1	1963
*The Forests of Wyoming	Resource Bulletin INT-2	1963
*The Forest Resources of Colorado	Resource Bulletin INT-3	1964
Output of Timber Products in Montana, 1962	Research Paper INT-11	1964
Forest Products Output in Utah and Nevada, 1962	Research Paper INT-12	1964
Output of Timber Products in Idaho, 1962	Research Paper INT-13	1964
*Timber Products Output in Colorado, Wyoming, and Western South Dakota, 1962	Research Paper INT-14	1964
*Timber Products Output in Arizona and New Mexico, 1962	Research Paper INT-15	1964
Forests in Utah	Resource Bulletin INT-4	1965
Site Index Curves for Engelmann Spruce in the Northern and Central Rocky Mountains	Research Note INT-42	1966
*New Mexico's Forest Resource	Resource Bulletin INT-5	1966
*Arizona's Forests	Resource Bulletin INT-6	1966
Timber and Timber Industries in the Rocky Mountain States	Resource Bulletin INT-7	1967

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U. S. FOREST SERVICE
RESEARCH PAPER INT-48
1968

High-Temperature Drying of Lumber--a Review

by

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HIGH-TEMPERATURE DRYING OF LUMBER--A REVIEW

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HIGH-TEMPERATURE DRYING OF LUMBER--A REVIEW

The worldwide research effort devoted to the high-temperature drying of wood has contributed greatly to our understanding of this process. However, the pertinent information is so widely scattered that much of it may be inaccessible to many persons.

The object of this report is to summarize present knowledge on the convective high-temperature drying of lumber and to indicate existing gaps in this knowledge. A report entitled "Bibliography of high-temperature drying of lumber" (26)[1] lists practically all of the publications on which the present report is based. The drying of veneer and high-temperature drying using other methods of heat transfer, such as hot platens, hot oil, and high-frequency energy are not discussed.

The term "high-temperature drying" when applied to the drying of lumber includes two processes carried out with the dry-bulb temperature above the boiling point of water. In one, the superheated steam process, the wet-bulb temperature is maintained at 212° F. (100° C.), and air is excluded. In the other, a mixture of air and steam is used and the wet-bulb temperature is below 212° F. (100° C.). The present commercial practice in this country is to use a mixture of air and steam; however, this process is based on earlier use of superheated steam as the drying medium.

HISTORICAL DEVELOPMENT

An early patent for an "Apparatus for drying and seasoning lumber by superheated steam" was granted to C. F. Allen and Luther W. Campbell (2) in 1867. The use of superheated steam was proposed again in 1875 by Bulygin (1) of Russia; in 1897 by Möller and Pfeiffer (29) in Germany; and in 1918 by Tiemann (36) of this country. As a result of Tiemann's work, a few superheated steam kilns were installed and operated in the Pacific Northwest for the commercial drying of softwoods. These kilns did not contain fans, instead circulation was achieved by steam jets. Rapid deterioration and high maintenance costs of the kilns forced their abandonment.

According to Egner (7), dry kilns capable of operating in the high-temperature range were available in a few European countries in 1930. These kilns corroded excessively and did not produce quality material, especially with green hardwood species.

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[1] Numbers in parentheses refer to Literature Cited at end of this paper.

Fischer and Czepek (9) pioneered development of the present-day high-temperature dry kilns during 1939 to 1944 when they carried out a number of experiments using small electrically heated kilns. Fans provided air circulation and the test material was heated in a saturated atmosphere before the drying process was started. They achieved astonishingly short drying times for coniferous species at temperatures of 248° F. (120° C.). After World War II, other German scientists studied hot-air drying and developed commercial equipment based upon the work of Fischer and Czepek.

FUNDAMENTAL ASPECTS

High-temperature drying, as practiced today, is fundamentally no different than kiln drying at any other temperature. It is simply a batch-type, forced convection drying process. However, the relative importance of various parameters changes with temperature and failure to recognize these changes has led to some confusion about high-temperature drying.

The Stages of Drying

Several investigators have observed two or three stages in high-temperature drying. These stages have been based on the drying rate and the wood temperature. Kollmann and Schneider (20) present an excellent summary of three stages.

The first stage of drying--the constant rate period--occurs only if the initial moisture content of the wood is above the fiber-saturation point. Evaporation takes place at the surface and the drying rate depends only on the external drying conditions--temperature, relative steam content, and the velocity of the drying medium. The drying rate can be calculated by using the rate of heat transfer, because heat and mass transfer must be equal during the constant rate period. The length of time during which constant rate drying takes place depends on the ability of the wood to supply liquid to the surface.

During the constant rate period, the wood temperature does not exceed the wet-bulb temperature, 212° F., in pure steam at atmospheric pressure.

When the wood can no longer supply water so that free water is present over all of the surface, the drying rate slows down and surface temperature starts to rise above wet-bulb temperature. This marks the beginning of the second stage of drying, frequently called the falling rate period.

Heat transfer into the wood and vapor movement out of the wood control the drying rate. It is believed that a zone of evaporation is formed inside the wood and that this zone moves from the surface toward the interior as drying proceeds. The increasing distance from the surface increases the resistance to heat and moisture flow, explaining the falling rate that is observed. The temperature and pressure at various depths inside the wood will depend on the relative ease of heat and mass transfer and the moisture content at the depth of interest.

When the wettest portion of the wood falls below the fiber-saturation point, the third stage of drying begins. This is also a falling rate period. The third stage continues until all of the wood is in equilibrium with the drying atmosphere.

The second and third stages are discussed in detail by [illegible] Hann (11).

Moisture Movement

Tiemann (37) pointed out that the quickest way to remove free water from [illegible] the material above the boiling temperature. The free water than vaporizes as rapidly as the necessary heat is supplied to the wood. However, the hygroscopic moisture cannot be boiled off and evaporation will be much slower below the fiber-saturation point. Tiemann also stated that the temperature in the wood could not exceed 212° F. as long as free water existed if the drying was done at atmospheric pressure. After the free water has vaporized, the material temperature will begin to rise until ultimately it attains the temperature of the superheated steam. He failed to state, but undoubtedly realized, that the pressure in the wood also could not exceed atmospheric pressure if the temperature in the wood stayed at 212° F. when free water was present.

Tiemann pointed out that the evaporative capacity of the superheated steam is dependent upon the amount of steam contacting the lumber and the number of degrees the steam is superheated. If the drying rate is slow enough, free water will be brought to the surface by capillary flow; however, if the drying rate is too rapid, the continuity of the capillaries will be broken and free water flow to the surface will cease. After capillary waterflow ceases, water-vapor diffusion becomes the only means by which moisture can move from the interior to the surface. The chief disadvantages to the use of superheated steam are the extreme speed with which it loses its superheat and becomes saturated and the large amount of energy required to heat the lumber.

However, Czepek (6) states that when wood is heated above 212° F. vapor diffusion occurs and there is almost no capillary movement of moisture. The movement of water vapor from inside to outside is also facilitated by the vapor pressure gradient as it relates to the drying atmosphere. He hypothesized that the flow of moisture through the wood is much greater at temperatures above 212° F. than at temperatures below 212° F.

According to Egner (7), however, moisture moves through the wood by both vapor diffusion and capillary forces. He cited temperature distribution curves obtained from wood cross sections as proof of the capillary movement of water in wood above the fiber-saturation point.

Egner also states that high-temperature drying using either superheated steam or steam-air mixtures is essentially the same as conventional drying. However, in the temperature range above 212° F. the term relative humidity should be used with reservation and he proposes the term "relative vapor content" as all humidities cannot be attained in this temperature range. He says that there is an increasing plasticity of the wood at high temperatures, which permits adjustment of some of the drying stresses. As a result, wood, so dried, fails to develop checks and other types of seasoning degrade.

Equilibrium Moisture Content

Keylwerth (13) investigated the relationship between wood moisture content and superheated steam in the temperature range above 212° F. at atmospheric pressure for spruce and beech. Also, he extrapolated the hygroscopic isobars for temperatures below 212° F. to a temperature of 200° F. [illegible]

equilibrium moisture content of approximately 7 percent in pure superheated steam. He pointed out that drying by superheated steam could be controlled by the dry-bulb temperature at atmospheric pressure, because the wet-bulb temperature would always be at 212° F. He also recognized that an absolute pressure differential might exist between the interior of the wood and the surface, due to the restriction of the rate of vapor movement by wood. The existence of such a pressure differential could influence the drying rate.

Koehler (17) presented graphs of relative humidity-equilibrium moisture content for temperatures up to 212° F. Eisenmann (8) published sorption isotherms for the range above 212° F. and established that there is hygroscopic equilibrium in this range at normal atmospheric pressure. Kauman (12) also developed charts of the temperature-relative-humidity-equilibrium wood moisture content for temperatures up to 400° F.

External Mass and Energy Transfer

Kollman and Schneider (20) studied the influence of circulation rate on lumber dried in superheated steam. In order to determine how velocity influences the rate and mechanism of drying, they carried out systematic experiments with pure, superheated steam and with a steam-air mixture. Velocities ranged from 230 to 2,100 feet per minute. For the first stage of drying (constant rate period), the drying rate increased as the 0.5 to 0.6 power of the velocity. In the following stage of falling drying rate, the effect of flow velocity became steadily smaller but remained discernible to 20-percent average moisture content. Because of the high heat transfer rates needed to maintain the rapid drying rates possible in high-temperature drying, especially during the constant rate period, the flow velocity is of much greater importance than in kiln drying at normal temperatures.

EVALUATION OF HIGH-TEMPERATURE DRYING

Few studies of high-temperature drying have been of an evaluation type, although much information has been gleaned from investigations having other objectives. There is a certain risk in generalizing from knowledge obtained in the drying of a particular species under particular conditions. However, a summary of this information should be of value to those engaged in research.

ADVANTAGES

Probably the most important advantage of high-temperature drying is the speed of drying; only about one-fourth of the usual time is required (35). Thus a smaller number of high-temperature kilns would be needed to dry the same quantity of lumber, which also will give a space savings (10).

Another advantage is the savings due to reduced inventory. Material can be processed rapidly, thereby reducing overhead costs and the necessity of maintaining a large inventory in order to satisfy immediate orders. Inventory reduction would also mean a savings in space.

Keylwerth (14) has stated that the normal energy required for superheated vapor kilns is 1.2 to 1.5 kilowatt hours per kilogram (2.2 pounds) of water evaporated, while low-temperature kilns require 2 to 4 kilowatt hours per kilogram.

Sharma and Bali (33) noted a significant reduction in the shrinkage of toon--a member of the mahogany family--dried at high temperature. Tangential shrinkage was more than radial shrinkage and volumetric shrinkage was not significantly different. High-temperature drying appeared to reduce shrinkage in western redcedar shingles dried below 10-percent moisture content (30).

Many investigators have reported a reduction in the equilibrium moisture content for high-temperature dried material. Koehler and Pillow (18) in 1925 compared air-dried Sitka spruce test specimens with specimens that had been exposed to 220° F. and 280° F. for periods up to 8 days. They noted a marked reduction in equilibrium moisture content in the specimens heated at 280° F., and a like reduction, though considerably smaller, in the specimens heated at 220° F. The major portion of the reduction occurred during the first 3 days of treatment and amounted to 2 percent for the material dried at 220° F. and 5.5 percent for the material dried at 280° F. Keylwerth (13) compared the equilibrium moisture content of material dried in pure steam at 240° F. with material dried at 150° F. In a normal climate, the equilibrium moisture content for the wood dried at 240° F. was 10.4 percent and for the wood dried at 150° F. was 12.2 percent.

DISADVANTAGES

The disadvantages of high-temperature drying can be grouped into two broad categories, those attributable to (a) the kiln, and (b) the quality of the dried material. Among the disadvantages attributed to commercial kilns are: higher initial cost, greater power requirement, and a greater heating capacity (16). Although no cost data are available, it has been assumed that costs for high-temperature kilns are greater because of the need for higher quality construction material to reduce heat loss and resist corrosion. In high-temperature drying, a relatively high airspeed is required to rapidly supply heat and to remove the water brought to the wood surfaces (23). Such airspeeds call for more installed power or, perhaps, the installation of additional fans, hence, greater costs. Also, greater heating capacity is necessary to quickly reach and maintain the desired high temperatures.

The quality of high-temperature-dried material entails an evaluation of the physical, mechanical, and chemical properties of the material. Probably the most obvious change in high-temperature dried wood is in the coloration. Many investigators have commented on the fact that material dried above 212° F. becomes a light brown or "toasty" color. If the material is surfaced, most of the discoloration is removed. Kollman (19) states that this discoloration is affected more by the wood moisture content and the drying humidity than by the drying temperature. Another change in physical appearance is knot dropout. Intergrown knots are not affected by temperatures above 212° F.; However, encased knots, resulting from dead branches, have a consistent tendency to drop out.

Because of the very rapid drying in high-temperature kilns, a steep moisture gradient is attained during the drying period (34, 25, 15). This severe moisture gradient and certain associated drying defects make this drying method unsuitable for the drying of many hardwoods from the green condition. However, air or predried hardwoods have been satisfactorily dried at high temperature (4). The moisture gradient may carry over in the material after it has been removed from the kiln and some of the time advantage accruing through the fast drying may be lost if the material is fully conditioned. The rapid drying and steep moisture gradient are also presumed responsible for the severe casehardening reported by Calvert (3).

It is recognized that exposure of wood to high temperatures for moderate periods of time or to moderate temperatures for long periods of time can effect a decrease in the dry weight of the wood (28). Koehler and Pillow (18) state that exposure to 280° F. for periods up to 8 days also caused a 5-percent reduction in specific gravity. Whether such a reduction in specific gravity occurs in high-temperature-dried material, where the exposure time at a temperature of 230° F. is considerably less, is not known.

Practically all of the mechanical properties of wood have been used to evaluate the effects of high-temperature drying.

Keylwerth (13) obtained higher average values for modulus of elasticity, maximum crushing strength, and modulus of rupture for the high-temperature-dried material than for the conventionally dried material. However, conventionally dried material was higher in impact strength and maximum stress in tension perpendicular to the grain. His spruce material was dried in pure steam at 240° F. This drying condition may account for the discrepancy between these results and later investigations. The control material was dried at 150° F.

Comben (5) stated that superheated steam drying had a negligible effect on the strength properties of obeche, abura, and Scots pine. Mahogany had an appreciable reduction in toughness and impact strength as well as an increase in brittleness.

Egner (7), working with spruce in Germany, obtained results that indicated high-temperature drying had no effect on the impact bending strength. Leont'ev et al. (24) tested pine dried in superheated steam at 212° F. and obtained approximately a 7-percent reduction in compression parallel to the grain, work in impact bending, and shear along the grain. In later work, Krecetov and Tsarev (22) determined that impact bending strength was reduced approximately 20 percent after exposure for 26 hours to 241° F., 28 percent after exposure to 230° F. for 28 hours, and 32 percent after exposure to 232° F. for 32 hours.

Salamon (31, 32), and Kozlik (21) have studied the effects of high-temperature drying on Douglas-fir and western hemlock. For Douglas-fir dried in superheated steam, as compared with conventionally dried Douglas-fir, Salamon obtained reductions in fiber stress at proportional limits of 5 to 16 percent, in modulus of rupture of 9 to 17 percent, in modulus of elasticity of 3 to 7 percent, and in maximum crushing strength of 8 to 13 percent. For Douglas-fir dried in an air-steam mixture, the reductions were: fiber stress at proportional limit, 7 percent; modulus of rupture, 13 percent; modulus of elasticity, 8 percent; and maximum crushing strength, 2.5 percent. Salamon obtained significantly higher values for the high-temperature dried western hemlock than for the conventionally dried western hemlock.

The values obtained by Kozlik (21) for Douglas-fir showed a 25-percent reduction in toughness for material dried at 215° F. and at 230° F. as compared to material dried at 90° F. and at 150° F. Modulus of rupture values showed a reduction of 12 percent in material dried at 90° F. as compared to material dried at 215° F. However, there was no significant difference in such values between material dried at 90° F. and material dried at 195° F. Radial and tangential shear values were reduced 15 to 20 percent for the material dried at 215° F. as compared with material dried at 90° to 150° F. Modulus of elasticity was least affected by temperature, being reduced 5 percent between material dried at 215° F. and material dried at 150° F. For western hemlock, toughness was most affected, being reduced 19 percent in tangential and 15 percent in radial toughness for specimens dried at 230° F. Modulus of rupture values were reduced 12 percent for the high-temperature-dried wood. Fiber stress at proportional

limit was slightly affected by the drying temperature, and modulus of elasticity values had a 4-percent reduction for the 230° F. compared with the 90° F. material.

Calvert (4) reported a 5-percent reduction in modulus of rupture after high-temperature drying, but no effect on toughness in red and white pine. Control material was conventionally kiln dried. For eastern hemlock, there was no difference in the modulus of rupture between the high temperature and the conventionally dried material and toughness values were greater for the high-temperature-dried specimens. Yellow birch and hard maple, high-temperature-dried, had an increase in all strength values.

In addition to mechanical tests, Egner (7) determined that high-temperature drying did not adversely affect the wear and tear (a special test) of spruce. He was able to glue satisfactorily high-temperature-dried spruce and beech, using casein, urea, melamine, phenol, and resorcinol adhesives.

The effect of high-temperature drying on the chemical makeup of wood has also been studied by Salamon (31). For western hemlock, there was no change in the lignin content and only a slight decrease in holocellulose and in the 1-percent alkali-soluble hemicellulose in high temperature-dried material.

MacDonald and Maclean (27) determined that western redcedar shingles could be dried at 285° F. without appreciable degrade on the chemical extractives that contribute to their durability.

SUMMARY

Although the process dates back to the last half of the 19th century, the high-temperature drying of lumber has become an established commercial practice only in the last 25 years. Even today the use is limited but interest is high.

Past research has shown that the mechanism of moisture movement during the constant rate and falling rate periods is not clearly understood; that flow velocity is more important in high-temperature than in conventional drying; and that equilibrium moisture content of wood at high temperatures is lower than at room temperature.

Reported advantages of high-temperature drying include short drying times, reduced inventory, lower energy requirements, reduction in shrinkage, and a lower equilibrium moisture content in use.

Disadvantages reported are higher initial equipment cost, greater power requirements and heating capacity, discoloration of the wood, knot dropout, conditioning problems, strength loss, and greater degrade with some species.

However, all results are based on limited studies involving only one or a few species and generally not employing equipment specifically designed for high-temperature drying. The influence of flow velocity and temperature on drying rate, defects, color change, and strength loss during the various stages of drying needs to be established for various species before high-temperature drying can be fully evaluated.

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Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Project headquarters are also at:

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RESEARCH PAPER INT-49, 1968

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PROJECT FIRE SCAN
FIRE MAPPING FINAL REPORT

April 1962 to December 1966 (Work Unit 2521A)

U.S. Department of Agriculture—Forest Service
Intermountain Forest and Range Experiment Station
Northern Forest Fire Laboratory
Missoula, Montana

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ACKNOWLEDGMENT

The authors here give special recognition to *Robert A. Cook* Forestry Research Technician, and *Eldon R. Down*, Aircraft Pilot, for the long and difficult hours they spent in performing fire-mapping missions required in support of this test program.

The authors gratefully acknowledge financial, technical, and cooperative assistance by several agencies and organizations in accomplishing the tasks included in this project. Among them are:

Department of the Army, Office of the Secretary of the Army

Infrared Physics Laboratory, Institute of Science and Technology, University of Michigan

HRB-Singer, Incorporated

State of Montana, Forestry Department

U.S. Forest Service National Forest Administration

The Electronic Command, U.S. Army Materiel Command

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PROJECT FIRE SCAN
FIRE MAPPING FINAL REPORT

April 1962 to December 1966

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Robert L. Bjornsen
Forrest H. Madden
Ralph A. Wilson

THE USE AND SYSTEM REQUIREMENTS OF
INFRARED SCANNERS IN MAPPING WILDFIRES
(Work Unit 2521A)

Prepared for
Department of the Army, Office of Civil Defense-OSA
under
Contract No. OCD-OS-62-174
and
Contract No. OCD-PS-66-17

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INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
U.S. DEPARTMENT OF AGRICULTURE—FOREST SERVICE
NORTHERN FOREST FIRE LABORATORY
MISSOULA, MONTANA

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INTRODUCTION

"Nuclear weapons have greatly increased the potential for wartime destruction by fire. Depending upon weapon yield and height of burst, the area subject to immediate ignition and burnout from a multimegaton nuclear weapon has been estimated to be between 450 and 1,200 square miles. Ultimate fire spread may be as much as 10,000 square miles under certain conditions. The vast areas over which ignition and burnout can occur with multimegaton weapons makes it virtually certain that rural as well as urban areas would be involved in fire in many regions.

Fires starting in either wildlands or built-up areas can spread from one to the other. Such fires are becoming increasingly common. The Bel Air fire in Los Angeles in 1961 burned 6,090 acres and destroyed about 505 buildings. In the spring of 1962, fires in New Jersey burned 186,000 acres, caused the death of 7 persons, and destroyed about 500 homes and buildings. In the fall of 1964, the Coyote fire near Santa Barbara, Calif., burned 67,000 acres of valuable watershed and destroyed at least 106 homes."[1]

Information about a fire's perimeter is a prerequisite for the control of large fires, whether caused by nuclear war, lightning, or man's carelessness. Visual aerial reconnaissance is usually limited by smoke. Location of a fire's perimeter with respect to surrounding terrain is difficult to determine at night by visual means. The alternative is use of slow-moving ground scouts who must oftentimes traverse rugged terrain either in vehicles or on foot.

A promising development, which combines the advantage of aerial observation with the ability to penetrate darkness and smoke, is the airborne infrared scanner. Particles associated with forest fire smoke cause serious scattering of light rays in the visible spectrum. At infrared wavelengths, this scattering is minimal, and useful information about a fire can be obtained. Simplified calculations indicated the amount of scattering of infrared energy in the 4.5- to 5.5-micron range by forest fire smoke would be tolerable. Tests conducted during 1962 through 1964 verified these calculations.

[1] *Countryman, C. M. Mass fire characteristics in large scale tests. Fire Technol. 1 (4): 303-317, illus. 1965.*

SCOPE OF WORK

In April 1962, Work Order OCD-OS-62-174 was negotiated between the Department of Defense, Office of Civil Defense, and the Department of Agriculture, Forest Service, to perform the following services:

"In consultation and cooperation with the Department of Defense, Office of Civil Defense, the Department of Agriculture, Forest Service, shall develop and test a heat sensing system that will locate fires, map the perimeters thereof, and measure the rate of fire spread generally in accordance with Intermountain Forest and Range Experiment Station proposal dated February 21, 1962. The practicability of using an airborne, infrared mapper for these purposes, and feasibility of the procedures developed during the course of this research, shall be experimentally tested by mapping actual raging forest fires and comparing the results with aerial patrol and ground observation methods now in use. There should be endeavors to classify timber stands, on a basis of species tolerance and stocking level or otherwise, as a means of indicating the cover density of the various kinds of timber."

In May 1964, Work Order No. OCD-OS-62-174 was amended (Amendment No. 8), and the revision provided a breakdown of the current scope of work by subtasks and added studies to the scope:

"In consultation and cooperation with the Office of Civil Defense, Office of the Secretary of the Army, the Department of Agriculture, Forest Service, shall conduct the following specific studies:

Subtask 2521A (I)—Feasibility Study of Airborne Infrared Device for Fire Detection and Mapping. *Determine the feasibility of using an airborne infrared device for fire detection and mapping in forest areas.*

Subtask 2521A (II)—ARPA Task No. 1 *Measure detection probability with an infrared scanner on small charcoal fires from a fixed elevated position at vertical angles from 50-60 degrees.*

Subtask 2521A (III)—ARPA Task No. 2 *Measure detection probability as a function of vertical angle from an airborne scanner on small charcoal fires in forests of the white pine-cedar-hemlock type in northern Idaho and in the Douglas-fir type found on the western slopes of the Cascade Mountains.*

Subtask 2521A (IV)—ARPA Task No. 3 *Measure detection probability on real fires utilizing an airborne scanner in systematic search of forested areas."*

In the fall of 1964, because of separate interests of the OCD and ARPA, the project was divided into two sections—fire mapping and fire detection. Subsequently, the fire detection subtasks II, III, and IV of OCD-OS-62-174 were replaced by ARPA Order No. 636.

Amendment No. 10 dated August 21, 1964, to Work Order No. OCD-OS-62-174 added the following to the Scope of Work:

"**Subtask 2521A (V)—Preliminary System Development**

a. Analyze intelligence requirements and collect data and determine operational requirements for mapping rural fires.

b. Analyze nuclear war environment requirements and determine operational requirements to support Civil Defense operations.

c. Analyze telemetry-ground readout system requirements and develop preliminary specifications.

d. Perform mapping missions in suburban wildfire analysis for applicability to Civil Defense operations, and develop procedures of employment of IR systems in suburban wildfire situations.

e. Develop methods of measuring rate of spread of fire."

Work Order OCD-PS-66-17, Work Unit 2521A, negotiated in September 1965, obligated the Department of Agriculture to furnish the following services to the Department of the Army, Office of Civil Defense:

"a. Analyze intelligence requirements and collect data and determine operational requirements for mapping rural fires.

b. Evaluate HRB-Singer pre-prototype airborne infrared scanner.

c. Analyze telemetry-ground readout system requirements and develop preliminary specifications.

d. Perform mapping missions in suburban wildfire analysis for applicability to CD operations and develop procedures of employment of Infrared systems in suburban wildfire situations.

e. Develop methods of measuring rate of spread of fire."

PROJECT FIRE SCAN PROGRAM DEVELOPMENT

A study of airborne infrared (IR) line scanners as a tool for use in forest fire detection began at the Northern Forest Fire Laboratory in 1962. An AAS/5 scanner, on loan from the Electronic Command, U.S. Army Materiel Command, produced a thermal map in the 3- to 5.5- micron infrared spectral range of the terrain beneath the aircraft.[2]

During the fall of 1962 we flew this scanner over a 300-acre controlled slash fire when a dense, deep smoke blanket prevented visual mapping. The smoke did not cause any apparent degradation of the IR image of the fire or the surrounding terrain (fig. 1). The experiment confirmed our assumptions about the transparency of smoke in the IR region and demonstrated the potential of IR scanners for gathering intelligence on large fires.

A study of operational feasibility, based on results of this test, was initiated to determine details of equipment requirements, operational methods, and training needed to implement IR mapping of wildland fires.

The AAS/5 infrared detection set fell far short of meeting our requirements for an operational system. Imagery was recorded on 35-mm. panchromatic film. The processing and printing necessary, prior to obtaining useful data, required an intolerably long time lag (2 to 4 hours) between gathering of intelligence and making it available to the user. The angular resolution of the system was inadequate to record details of the terrain required for effective interpretation. The 80° scan angle was inadequate to provide the coverage needed in fire-mapping operations. And finally, the dynamic range of the system was inadequate to handle the extreme contrast between normal variations of terrain temperature and the very hot areas of a going fire.

We modified the AAS/5 scanner to meet our requirements. The 35-mm. strip film camera was replaced by a Polaroid[3] camera that could produce prints immediately. The scan angle was increased to 120°; the focal length of the optical system was increased; and the detector (the field stop in the system) was reduced in size. The bandpass of the video electronics was widened to accommodate the higher resolution of the optical system; and the cathode ray tube printer was replaced by one capable of a much smaller spot size. We tried to overcome the limited dynamic range of the system by including a logarithmic amplifier. These modifications produced a system that consistently produced reasonably high-quality imagery when operated by Laboratory personnel.

During the summer of 1963, this modified scanner was flown over nine fires. On two flights we dropped the Polaroid prints immediately to an IR interpreter in the fire camp. The fire suppression forces could use this intelligence immediately. The 1963 tests demonstrated the desirability of the immediate readout Polaroid prints and the suitability of the airdrop delivery method on relatively small, back-country fires.

The limited experience gained during 1963 indicated need for an expanded study of fire mapping to answer the following questions:

1. What are the intelligence requirements for suppression of large fires, and how many of these requirements can be satisfied by using IR scanning techniques?

2. Is the airdrop of IR imagery suitable for all fire situations or will a telemetering capability be required?

[2] *For a detailed description of the fire detection effort see: Wilson, Ralph A., and Nonan V. Noste. Project Fire Scan fire detection interim report, April 1962-December 1964. U. S. Forest Serv. Res. Pap. INT-25, 55 pp., illus. 1966.*

[3] *Mention of trade or brand names is solely for identification and does not imply endorsement of products mentioned, nor does it imply nonendorsement of unnamed products.*

Figure 1.—Kelly Creek prescribed fire, 1962: A, Oblique photographs; B, infrared map.

3. Will fire mapping be used primarily in initial stages of fire control? will it be required during control operations? and what is its utility during mopup?

4. At what altitude should fire-mapping missions be flown?

5. At what times of day should IR missions be flown?

6. What are the performance requirements for an operational fire mapper?

7. What will be the reaction of trained fire control officers to this new tool? how will they use it? and what is their evaluation of its utility?

In January 1964, preliminary criteria for an infrared fire-mapping set were prepared at the request of the Office of Civil Defense (see appendix I).

In preparation for the 1964 fire season, the IR equipment used during the 1963 season was installed in a Forest Service Aero Commander 500-B to be used exclusively for fire-mapping. Provisions were made for dispatching the unit to dangerous fire situations anywhere in the country. A cadre of Forest Service personnel from throughout the West was trained as IR interpreters so that their services would be available to support the small Laboratory team.

During the 1964 fire season, the infrared-equipped aircraft mapped 16 fires ranging in size from 10 to 215,000 acres. We flew 33 daytime and 16 nighttime flights. On 12 of these fires, the intelligence gathered was used by fire suppression forces. The situations encountered ranged from flat country grass fires to wilderness area fires in rugged terrain and heavy timber, to the rural-urban complex involving both brush fields and buildings. We worked closely with Forest Service fire suppression teams, State fire suppression agencies, the California Disaster Office, and the Los Angeles County Fire Department. The wide variety of conditions encountered during this season provided a sound basis for determining equipment re-

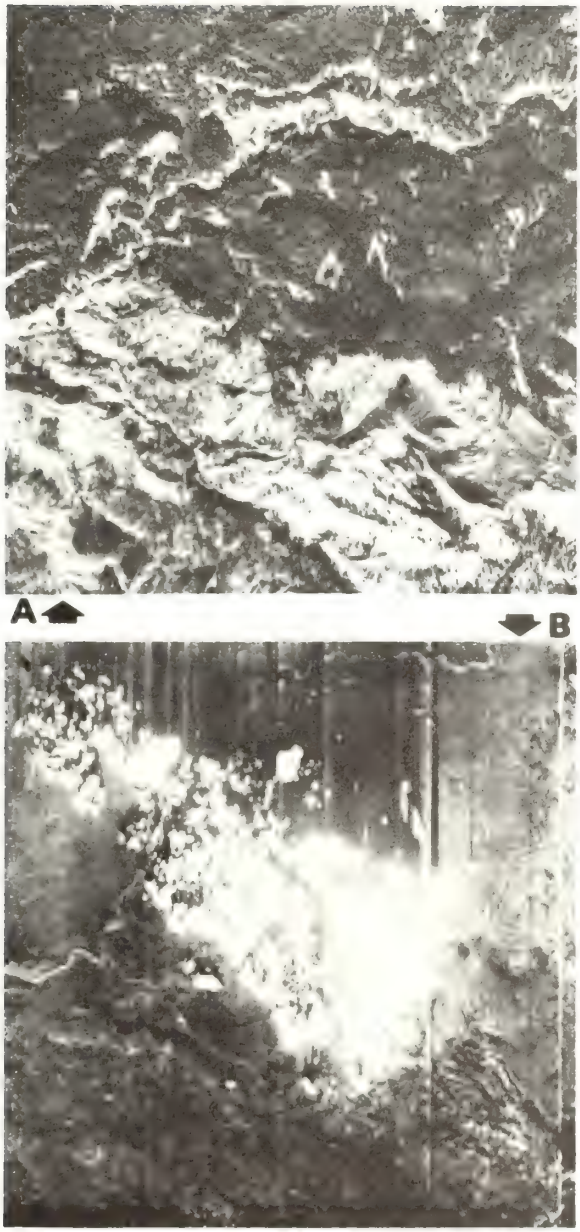

Figure 2. — Gravel Creek Fire, 1963: A, Conventional aerial photograph made prior to the fire and used for identifying terrain features recorded on IR imagery; B, IR image of fire clearly showing location of small spot fires outside of main fire perimeter.

quirements, personnel needs, and expected performance of the IR scanning system.

We needed to know how many fires might need to be mapped during any year, and the number of fires that might reasonably be expected to occur concurrently before we could prepare final system specifications. To obtain this information, we analyzed Forest Service fire records for the preceding 20 years.

Late in 1964, a contract was negotiated by the Office of Civil Defense with HRB-Singer, Incorporated, to design and fabricate an IR fire-mapping unit in accordance with preliminary design criteria prepared at the Northern Forest Fire Laboratory. We received the new scanner (HRB-Singer Reconofax XI) in the spring of 1965. The Aero Commander was modified for installation of this new unit, and preliminary flight tests were conducted during 1965.

The new prototype unit had several deficiencies. The amplifiers were unstable at high gain settings. The available gain was inadequate to make nighttime imagery. Amplifier saturation caused serious overshoot problems. Packaging of the electronics was not suitable for field servicing. These shortcomings had to be corrected before we could make adequate operational tests.

The equipment was returned to the manufacturer with detailed recommendations for modification. The needed modifications were performed during the winter of 1965. In the spring of 1966, the system was reinstalled in the Aero Commander and delivered to the U.S. Forest Service, Division of Fire Control, for field evaluation. Results of subsequent tests were highly encouraging.

INTELLIGENCE REQUIREMENTS FOR WILDLAND FIRE SUPPRESSION

Decisions necessary for effective fire suppression must be based on the dynamic characteristics of the fire perimeter, its relation to fuels, weather, topography, values threatened, and the availability of suppression forces. The mission of IR fire-mapping

should be to furnish the location of the fire perimeters at periodic intervals, rapidly enough and in sufficient detail to allow fire control officers to make informed decisions (appendix II).

The most important requirement is a picture of the fire edge in relation to such ground features as ridgetops, valley bottoms, streams, and prominent landmarks. Such pictures must show sufficient detail to enable the interpreter to determine the precise location of the fire edge, hotspots, spot fires, fuel type changes, and fuel breaks. Complete description of the fire and its behavior must include the following:

1. Extent and location of the entire fire edge, including both smoldering and flaming fronts.

2. Relative intensity of the fire along various portions of the fronts and the rate of fire spread.

3. Size and location of spot fires outside the main fire edge.

4. Location, size, and intensity of isolated hot spots within the main fire perimeter, especially those adjacent to the fire edge.

5. Location and adequacy of all firebreaks, both natural and manmade.

6. Size and location of unburned areas of fuel of 5 or more acres within the fire perimeter.

7. Existence and location of major fuel type changes for a distance of 1 or more miles outside the fire edge; i.e., changes between grass and brush, timber and brush, conifer and hardwood, blowdown and standing timber, water and land, rocks and timber, and rural or urban developments.

8. Location and extent of structures such as residences, bridges, factories, schools, and urban communities with respect to the fire front.

In figure 2 (Gravel Creek Fire), many of these characteristics can be seen in the infrared image.

Fire intelligence is a highly perishable commodity. During the active stages of a fire's spread, any description of its characteristics may have little operational value 4 hours later. The fire boss charged with responsibility for strategy decisions must know what the fire is doing *now. One prime requisite for any fire surveillance system is ability to deliver fire intelligence to the fire staff at the scene of the fire at the time when major strategic decisions must be made.*

Since infrared mapping systems produce a thermal image of the terrain being scanned, it is easy to differentiate between a hot fire and the surrounding terrain. Identifying fuel and topographic features is much more difficult. Before proceeding with a detailed discussion of the capabilities and limitations of IR scanners for collecting fire intelligence, it may be helpful to discuss some characteristics of IR scanners and the factors that affect their ability to depict surface features.

IR LINE SCANNERS

The IR line scanners used in fire-mapping operations consist essentially of a telescope with a suitable detector at its focal point. A rotating scanning mirror placed in front of the objective of the telescope causes the optical system to scan a line perpendicular to the aircraft flight path (fig. 3). As the aircraft moves forward along the track, sequential, contiguous lines are scanned. The output of the detector is amplified, converted to light, and printed on film. The printing device exposes a line across the film in synchronism with the rotating scanning mirror—X-axis. Film motion, in a direction perpendicular to the scan line at a velocity proportional to aircraft velocity and altitude, provides the Y-axis of the image (fig. 4). The scale of the resulting image is a function of the scan angle recorded and the altitude of the aircraft. Spatial resolution is determined

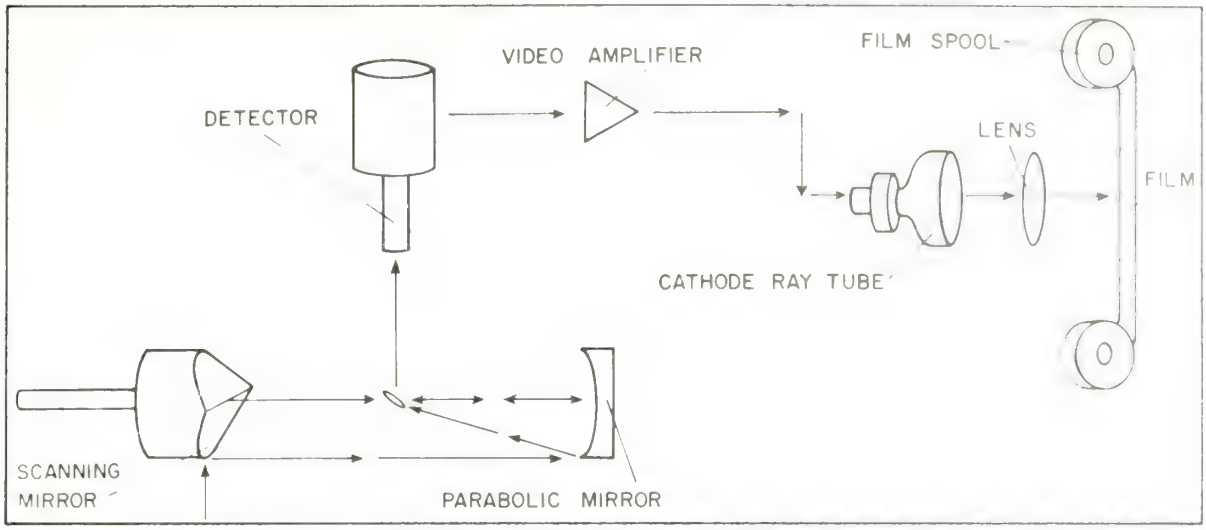

Figure 3.—Schematic of an IR scanner.

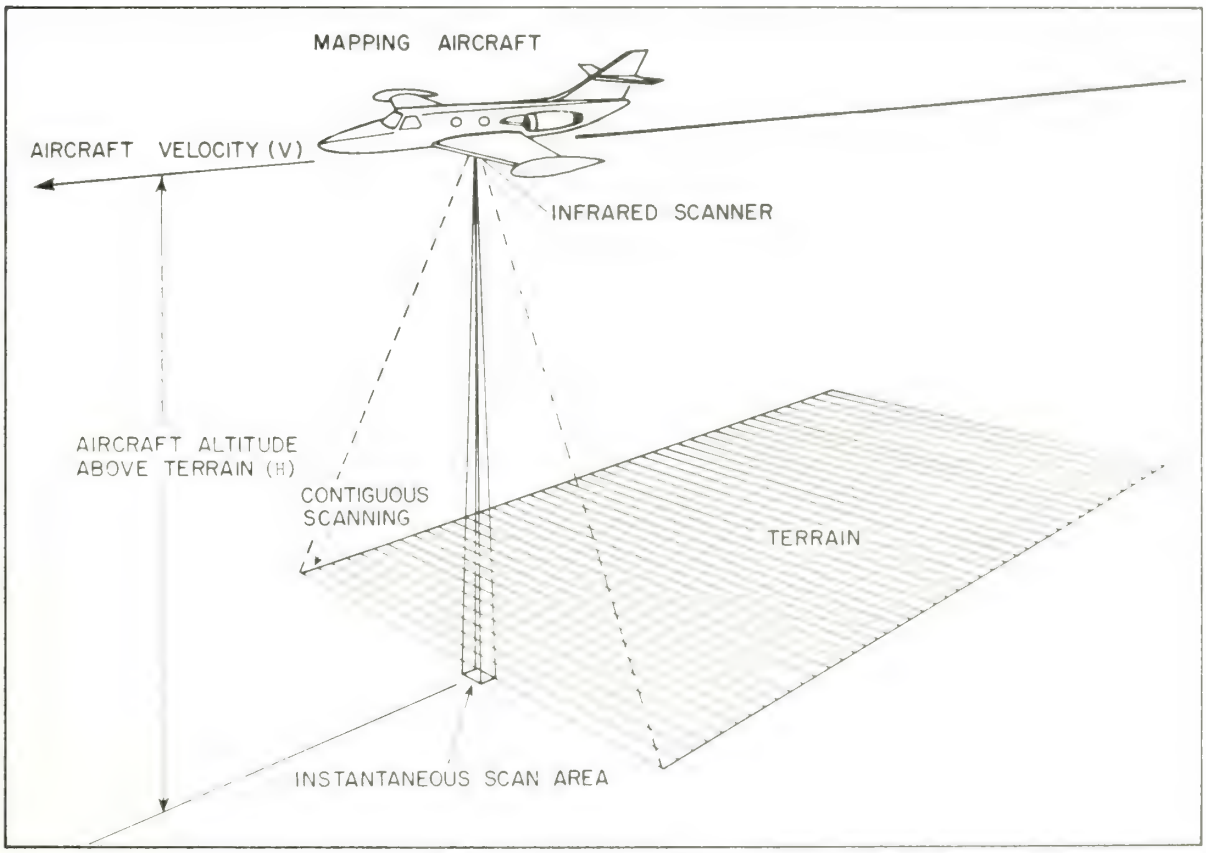

Figure 4.—Line scan coverage.

by the focal length of the optical system, the size of the detector, the minimum spot size obtainable in the printer, and the height of the aircraft above ground. The spectral response of the system is determined by detector characteristics and filters used. Distortions inherent in these systems are discussed in appendix III.

IR IMAGERY

The tone of any spot in an IR image is a function (usually nonlinear) of the energy arriving at the scanner aperture from the ground. On a positive image, light tones indicate more energy, dark tones indicate less. The tones on imagery made during darkness depend on the temperature of the terrain being scanned and variations in surface emissivity; i.e., the tonal contrast represents the apparent radiant temperature. During daylight hours, the image tone depends on the energy radiated from the surface and the reflected solar energy; it is a function of detector spectral response, solar insolation, surface spectral reflectance, surface temperature, and surface emissivity. For an object to be detectable on IR imagery, the energy radiated or reflected from it must be sufficiently different from the energy radiated or reflected from the surrounding terrain to produce a signal equal to or greater than the noise equivalent temperature of the system.

The temperature of some terrestrial features, such as large bodies of water, varies seasonally but shows very small diurnal variations. Most other objects exhibit both seasonal and diurnal variation in temperature. Objects having very low thermal mass follow diurnal air temperature variations fairly closely, whereas objects having much higher themal mass tend to lag behind the changes in ambient temperatures. These characteristics produce diurnal fluctuations in the tonal contrast of objects recorded on thermal IR imagery. These fluctuations can be most dramatically demonstrated by examining the diurnal temperature variations of three objects: (1) a land area, (2) a rapidly flowing river, and (3) a bridge across the river.

During a bright, clear day in summer the temperature of the bridge rises as insolation increases. There is some lag between the surface temperature of the bridge and the changes in insolation. As darkness approaches and insolation decreases, the temperature of the bridge gradually decreases. During the hours of darkness, radiant exchange between the bridge and the sky further reduces the bridge temperature. The next morning, as insolation increases, the bridge temperature will again rise. Temperature of the river remains constant throughout the period. Temperature of the land surface also changes from day to night, but at a slower rate than that of the bridge. Imagery made during one diurnal cycle goes through a complete reversal of tonal scale. The land-to-water and bridge-to-water tonal differences completely disappear during two periods.

Since these tonal shifts depend on insolation and nighttime radiative cooling, cloud cover and seasonal variations in insolation strongly affect the rates at which tonal changes occur. Although this water-land-bridge combination produces the most striking effects, the same shifts occur in all objects. The foregoing discussions assume a spectral response in the thermal IR only. During daylight hours, these effects are further compounded by solar reflection and variations in surface reflectivity and emissivity.

CAPABILITY OF IR SCANNERS FOR GATHERING INTELLIGENCE

Performance capability of IR scanning systems is usually specified in terms of resolutions of angle and temperature. Secondary considerations are the velocity-to-height ratio (V/H) and total field of view, which govern the field coverage rate. Even when precise laboratory measurements are made of the above parameters, it is very difficult to predict field performance.

If we are to predict an IR system's performance of such a complex task, the parameters of angular and temperature resolution are inadequate. At least six different defini-

tions of "angular resolution" and three of "temperature resolution" could apply, but none have been generally accepted as a standard, and none are adequate to describe performance of a scanning system.

The best available figure of merit (FM) of scanning systems is discussed in HRB-Singer's Report 1751.20-R-1, "Basic Design Considerations for an Infrared Scanning System," which uses the formula:

$$\text{Figure of Merit (FM)} = \frac{\text{System Modulation Transfer Function (MTF)}}{\text{System Noise Equivalent Temperature (NET)}}$$

The MTF is essentially the input spatial frequency that is reproduced at the output of the system. Usually it is not an analytic function; however, it is calculable and easily specified for any system. MTF is more precisely defined than "angular resolution." NET is that temperature difference that would give a signal at the detector equal to the system RMS (root mean square) noise. This is an *effective* radiometric temperature defined for each system by an explicit function:

$$T = f(E)$$

where E is the total radiant energy to which the detector responds. This figure of merit is dependent only on the internal components of the system and is independent of the field at which the scanner is looking.

With the known MTF and NET, and given an exact description of the terrain field's radiant intensity distribution, one can calculate exactly what will be displayed on the image photograph. However, no one can now provide the necessary radiometric description of forested environments.

The complexity of the terrain radiometric field can be demonstrated. The energy (same as E above) from all observable sources to which a scanner responds and which is emanating from every point (x,y) in the forest can be written functionally as follows:

$$E(x,y) = \int_{\lambda} P(\lambda)\, U(\lambda) \left[\in (\lambda,\alpha,x,y)\, N_1(\lambda, T(x,y)) + R(\lambda,\alpha,\beta,x,y) N_i(\lambda, T_i) \right] d\lambda$$

$P(\lambda)$ is the relative spectral response of a system and is known.

$U(\lambda)$ is the atmospheric transmission and is strongly dependent on weather conditions.

E can vary 50 percent because of relative humidity alone.

The emissivity, $\in(\lambda,\alpha,x,y)$, can be determined only empirically by direct observation of every material of interest and under all conceivable conditions. $\in$ varies from material to material according to surface roughness, moisture content, observation angle, wavelength, chemical composition, impurities, and other variables. $N_1(\lambda,T(x,y))$ is the analytic Planck equation and is calculable only if the temperature of every point to be observed is known. Generally, differences in energy, E, depend more strongly on $\in$ in the 8- to 14-micron region, where differences between materials at ambient temperatures are more easily observed. Fires are more easily observed in the 3- to 6-micron region, where differences in $N_1(T)$ usually account for the greater differences in E. $R(\lambda,\alpha,\beta,x,y)$ is the reflectivity of each point in the field. Same comments as on emissivity apply; also, R is strongly dependent on the illumination angle, β.

$N_i(\lambda,T_i)$ is the surface illumination from extraneous sources such as the sun. N_i is not difficult to estimate (on clear days) but not as simple as N_1 above. At night we assume $N_i=0$.

From the above considerations, the dismay of a scientist can be anticipated when he is asked, "Can this scanner see a dirt road in a grass field?" The only possible answer is "It might." If answers to the following questions are known, a better GUESS can be made. Is the dirt smooth and hard packed? Is the grass green and standing? Has the sun been shining continuously for the past several hours? Is the sun shining now? Did it rain last night? Do you wish to observe the road from a low altitude? If answers to all these questions are

"yes," then the *chances* of observing the road are *probably* better. How much better—who knows? Only when the exact composition and physical state of the road and grass field are given, and only when previous empirical data are available for those conditions, can reliable yes-no answers be given. Invariably, however, problems and questions of this type are qualitatively specified. At best, the answers *must* be qualified.

A V/H capability of .25 radian per second is adequate to meet fire-mapping needs. A system angular resolution of 4 milliradians and a temperature resolution of 2^{o} K. are the absolute minimum for fire-mapping; i.e., most of the information required can be obtained under optimum conditions. With an angular resolution of 1 milliradian and a NET of $\frac{1}{2}^{o}$ K. we feel that under most conditions the needed fire intelligence can be obtained.

Table 1 shows our "best guess" comparison of the adequacy of two different systems in meeting the requirements for fire intelligence.

Table 1.—Estimated performance of fire-mapping systems

	Operational altitude	Estimated performance*	
		$\Delta\alpha$=4 milliradians $\Delta T=2^{\circ}$ K.	$\Delta\alpha$=1 milliradian $\Delta T=\frac{1}{2}^{\circ}$ K.
	Feet		
Fire edge			
Overall perimeter	10,000 max.	Adequate	Adequate
Flaming front	10,000 max.	Adequate	Adequate
Rate of spread	≤10,000	Adequate	Adequate
Intensity (size)	10,000 max.	Adequate	Adequate
Firelines and breaks	4,000 min.	Poor	Probably adequate: $\Delta T=1/10^{\circ}$ K. would improve chances tremendously
Spot fires ahead of front	10,000	Poor, depends on timber cover and spot fire intensity and size	Much better, probably adequate. Still a matter of statistical chance
Fuels			
Hot spots within 300′ of fire edge	4,000 min.	Adequate	Adequate
Unburned fuels ≥5 acres	10,000	Very poor	Moderate; very dependent on ΔT; also prior knowledge of local area
Fuel types outside of fire	10,000	Poor	Probably adequate with prior knowledge of local area
Structural improvements	10,000	Adequate on basis of association with local surroundings	Very good

*Distances on ground are determined only with ±4 feet per 1,000 feet of altitude with 4-milliradian systems, and ±1 foot per 1,000 feet with 1-milliradian systems.

PROTOTYPE FIRE-MAPPING SYSTEM

The fire-mapping system developed under OCD Contract No. OCD-OS-62-174 was designed to meet the criteria prepared by Project Fire Scan (appendix I). The system consists of three major subsystems:

1. The Reconofax XI[4] IR scanner and remote control unit;

2. a test oscilloscope; and

3. a real-time viewer and Polaroid camera assembly.

RECONOFAX XI SCANNER

The IR scanner unit (fig. 5) contains the rotating optics, the detector-dewar-preamp assembly, the glow tube modulator assembly, and the 70-mm. film cassette. The cassette is easily removed for film processing through a panel in the side of the scanner. The port door (shown open in fig. 5) automatically closes when the scanner is not operating. The scanner's remote control unit (fig. 6) contains the video processing circuits and the system power controls.

The test oscilloscope originally supplied with the system was a 3-inch Tektronix Model 321 operating directly from the aircraft's 28 v.d.c.

The Reconofax XI IR scanner delivered to the Northern Forest Fire Laboratory in June 1965 was too unreliable even for flight testing. It was returned to the factory for temporary repairs in late August 1965. Upon return, tests on a few fires in California, followed by laboratory tests, furnished enough information for preparing an evaluation report,[5] which listed 39 recommended changes. A contract was negotiated with HRB-Singer, Incorporated, to modify the system in accordance with recommendations in this report. Twenty-three of the 39 items were deemed feasible and reasonable, considering the time and money available.

REAL-TIME VIEWER

While the Reconofax XI system was at the factory, the real-time viewer (fig. 7) was delivered to the Northern Forest Fire Laboratory for evaluation. The real-time viewer (B-scan) contained a single-frame Polaroid camera for photographing a high-resolution cathode ray tube (CRT). Construction of the viewer was considerably better than that of the original scanner.

The viewer was received without an internal high-voltage power supply. Because the normal supply had failed at the factory, the manufacturer furnished an external laboratory power supply for preliminary tests.

A dual phosphor (P-7) CRT[6] was supplied with the viewer to permit monitoring and photographing a single tube. The CRT manufacturer specifies a minimum spot size of .003 inch for the P-7 phosphor. The spot size was nearer .006 inch when installed in the printer. A .001-inch spot size is required to retain the desired scanner resolution.

When we found the required resolution could not be achieved with the dual phosphor CRT, the manufacturer replaced it with a P-11 phosphor CRT. The best laboratory measurement of spot size was .002 inch. In field operation the spot size was nearer .005 inch. Several factors caused degradation in spot size. The .002-inch spot size was measured under controlled conditions with optimum focus voltage and minimum noise and ripple. Under field operating conditions the

[4] *For detailed information on the original Reconofax XI scanning system see: Sobel, J. A., III. Prototype airborne infrared fire mapping set (U). HRB-Singer Final Research Report, Contract OCD-PS-65-54, OCD Subtask No. 2524B. 59 pp., illus. (Classified). 1965.*

[5] *"First Evaluation of the Reconofax XI," Northern Forest Fire Laboratory in-house report, November 5, 1965.*

[6] *A P-7 cathode ray tube has a dual phosphor coating with two spectral peaks. A medium short-persistence peak at 4400 Å is suitable for photographing when used with a blue filter. A long-persistence peak at 5580 Å with an amber filter is adequate for B-scan viewing.*

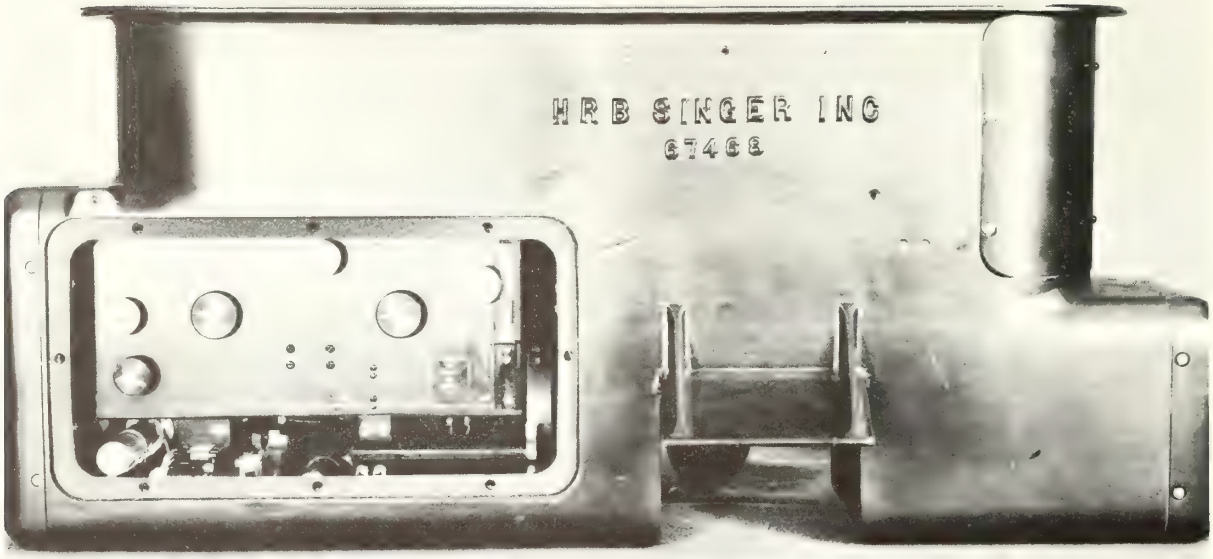

Figure 5.—Reconofax XI IR fire-mapping scanner.

focus voltage was 75 volts low, and the high-voltage power supply contained more ripple than the laboratory power supply that had been used for the controlled tests. The low-voltage power supplies created noise spikes and ripple in the video circuits. Ground loops and poor wire routing added noise and ripple to the video. Each condition increases spot size.

Figure 6.—Reconofax XI (mod 2) IR scanner's remote control unit.

CRT pincushion distortion[7] was about one-sixteenth inch when it was received. A permanent magnet pincushion corrector was purchased for $35.00 and installed on the CRT deflection yoke. Line curvature was not noticeable after the corrector was alined and locked in place.

The input to the viewer video amplifier was a.c. coupled without d.c. restoration (see appendix IV). Blocking occurs on the viewer imagery whenever the hot signal is large enough to alter the background reference level (indicated by arrows, fig. 8). Smaller video changes cause signals adjacent to the fire to lose contrast and detail. The variable voltage clipping in the scanner control unit successfully reduced the large signal amplitudes.

CAMERA

The viewer was furnished with a single frame Polaroid camera (Tektronix Model C-12). Northern Forest Fire Laboratory per-

[7] *Pincushion distortion occurs when the distance traveled by an electron varies as the electron beam moves across the face of the cathode ray tube. The amount of deviation, or curvature, from a straight line is used here as a measure of pincushion distortion. For further details see: Jenkins, Francis A., and Harvey E. White. Fundamentals of optics, Ed. 2, p. 143. 647 pp., illus. New York: McGraw-Hill. 1950.*

Figure 7.—Real-time viewer with dual Polaroid camera attached.

sonnel developed a unique camera, using parts from the C-12, to meet the requirements for immediate and continuous positive prints of fire imagery (figs. 9 and 10).

The dual Polaroid camera system contains a "flipping" mirror and lens assembly that projects the viewer cathode ray tube image sequentially onto two Polaroid film packs. The viewer gives control signals for the camera. The rear frame of the Tektronix Type C-12 camera was replaced by a new unit containing the flipping mirror and two Polaroid film packs. The flipping mirror is two first-surface mirrors mounted back to back and rotated to image the CRT face, first to one film pack and then the other. The mirror is driven in both directions by two rotary solenoids powered by the camera relay in the real-time viewer. (The camera relay is operated by the vertical sweep.) A panel on the back of the camera contains (1) two amber lamps to indicate which film pack is being exposed, (2) a green lamp to indicate when the shutter is open, and (3) a reset button to control the start of a frame by restarting the viewer vertical sweep.

A slate unit (fig. 10) records sequential frame numbers, time of day, and written information on the imagery. The slating mechanism is mounted on the base plate of the C-12 camera and is imaged through a beam splitter onto a ½-inch strip along the edge of the film. The slating unit folds down for access to the clock and writing surface.

Considerable effort was spent in making the camera compact. All wiring is internal;

Figure 8.—IR fire imagery showing shifts of d.c. level.

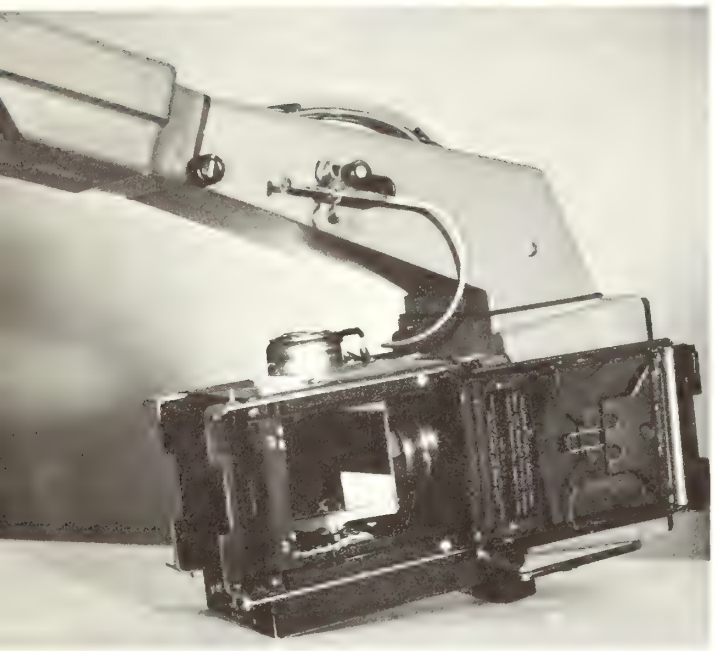

Figure 9.—Dual Polaroid camera with film back open.

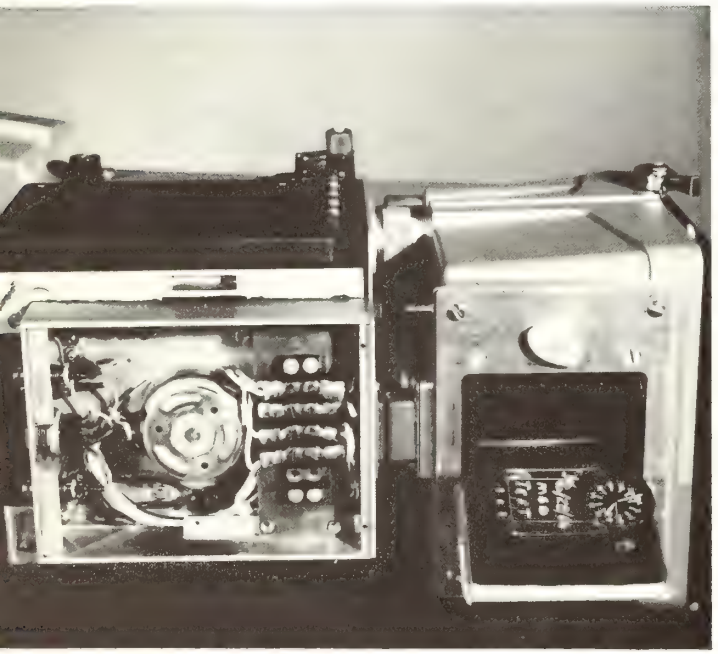

Figure 10.—Dual Polaroid camera with data slate door open.

connections are made automatically as the camera is closed. Camera focus, aperture, and shutter speed controls were not changed. Standard Polaroid film packs are easily loaded from either side of the camera. The installation on the real-time viewer is the same as mounting a camera on an oscilloscope.

MONITOR

Initial planning incorporated the system monitor into the printer as a dual-purpose viewer. When the dual phosphor CRT was replaced with the short-persistence CRT, a new monitor was required. Choosing a standard oscilloscope for the monitor let us eliminate the separate test oscilloscope. A Tektronix Type 422 portable oscilloscope (fig. 11) with a P-7 phosphor CRT was chosen for its compactness, versatility, and power requirements. The scope was modified to permit intensity modulating the cathode for B-scan operation. The viewer provided vertical and horizontal sweeps. The cathode may be disconnected for A-scan operation, or both B-scan and A-scan may be viewed simultaneously.

Two viewer modifications were made to provide signals for the monitor scope: a new video amplifier and an additional horizontal sweep amplifier were installed.

MODIFIED RECONOFAX XI

In June 1966, the Reconofax XI (mod 2) scanner was returned to the Northern Forest Fire Laboratory for 6 weeks of extensive

Figure 11.—Monitor oscilloscope.

testing. The scanner and remote control assembly (fig. 6) had been thoroughly modified. All wiring was replaced, new printed circuits were installed, and internal packaging was completely changed. The new scanner was fully reliable.

The modifications included a redesign of the video circuits to reduce the problems caused by large fire signals. D.c. amplifiers separated by a.c. coupling with d.c. restoration reduced reference level shifts (appendix IV). Amplifier gain was increased to 94 db for higher film contrast from low-level terrain signals. The 3-db bandwidth was fixed at approximately 650 kHz to enhance small terrain features. Large fire signals cause film and CRT phosphor saturation and reference level shifts; this causes loss of detail in imagery of fire perimeter and adjacent terrain. The amplitudes of high-energy fire signals can be restricted by voltage clipping circuits. Two methods of voltage clipping were used to reduce the effects of excessive signal:

1. A fixed voltage clipping level was built into the video amplifiers. No incoming signal can cause an output that exceeds this clipping level. This eliminates halation on the film caused by large signals as long as the d.c. reference is retained.

2. A variable voltage clipping circuit was added; it permits adjustment of the maximum signal level to meet changing terrain conditions. The variable voltage clipping circuit is unnecessary and can be removed from future systems having adequate fixed voltage clipping.

SYSTEM EVALUATION

The Reconofax XI scanner, real-time viewer, and monitor were combined for a series of laboratory tests. Angular resolution was measured using a hot, black source with 1-, 2-, and 4-mil apertures collimated and folded into the scanner. Angular resolution at the output of the preamp was between 1 and 2 milliradians, as measured from Polaroid pictures of an A-scan trace.

Total system angular resolution was determined by printing resolution targets on both 70-mm. and Polaroid film. Resolution on the 70-mm. film was between 3 and 4 milliradians. Inadequate focus of the CRT restricted the resolution of Polaroid film to about 4 milliradians in the 60° scan position and 8 milliradians in the 120° scan position.

Temperature resolution was measured as a noise equivalent temperature (NET) equal approximately to 2° K. The heat source for measuring NET was a single hot target equal to approximately one angular resolution element measured against an ambient temperature background. Target temperatures between 30° C. and 70° C. provided signals within the linear portion of the amplifier gain curve. Then

$$NET = \frac{T_t - T_b}{E_{spk}/E_{nrms}}$$

where:

T_t = the target temperature,

T_b = the background temperature,

E_{spk} = the peak signal voltage, and

E_{nrms} = the true rms value of the background noise without the target.

Contrast and intensity controls worked very well. The coarse and fine attenuation (contrast) controls permit excellent adjustment of signal amplitudes on both 70-mm. film and the B-scan. The contrast control on the B-scan is used only for initial setup. Separate intensity (brightness) controls for the 70-mm. and the B-scan permit individual d.c. adjustments to compensate for equipment drift.

A new problem with the scanner viewing angle became evident during the evaluation tests. Large fires seen by the scanner outside the desired 120° field of view disturbed the d.c. restoration level. A black streak across the image results (see arrows, fig. 8). The

scanning mirror always "sees" more than the desired 120° field of view unless vignetting is permitted. Small metal shields on the aircraft, restricting the total field of view to 120°, temporarily reduced the effects of this problem. Some vignetting of the desired signal occurs, but is not severe enough to be objectionable.

The scanner, real-time viewer, and monitor oscilloscope were installed in a U. S. Forest Service Aero Commander 500-B aircraft (fig. 12), which has a special scanning slot cut in the bottom of the fuselage for the Reconofax XI scanner.

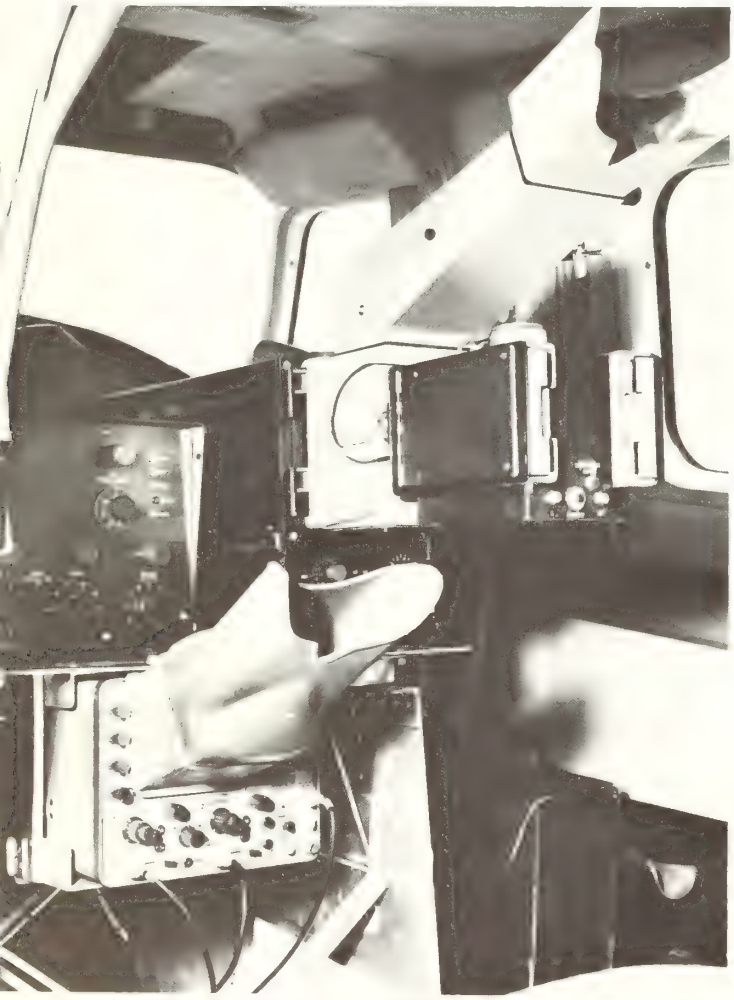

Figure 12.—Final installation of the fire-mapping system in the Aero Commander 500-B aircraft. The scanner is behind the seat in the lower right corner of the picture.

Angular and thermal requirements for fire-mapping systems are not well defined. Local test flights demonstrated system performance for comparison with the original design criteria (appendix I). Both day and night flights over resolution charts, airports, and urban areas were made to aid subjective decisions on system performance. Automobiles in parking lots, trailer courts, and aircraft engine nacelles were used to determine angular resolution after resolution charts were not resolvable. Water temperature gradients in a river and in factory cooling ponds were used to judge temperature resolution. The results were:

1. The system angular resolution was 3 to 4 mr. and was poorer than the desired minimum (appendix I).

2. The angular resolution of the 70-mm. and Polaroid film in the 60° position was approximately equal.

3. System temperature resolution of the 70-mm. and Polaroid film was about equal and was adequate for most fire-mapping missions.

Since no wildfires were available locally during the test period, the system was put into operation without prior evaluation over a fire. The fire-mapping system released to the Division of Fire Control, U. S. Forest Service, on July 13, 1966, consisted of:

1. A Reconofax XI (mod 2) IR scanner and remote control unit;

2. a B-scan, real-time printer with a dual Polaroid camera attachment;

3. a monitor oscilloscope; and

4. miscellaneous associated materials required to permit system operation.

OPERATIONAL CONSIDERATIONS

NAVIGATION

Any fires requiring IR mapping are partially or totally obscured by a dense smoke pall, which usually covers only the area directly above and immediately adjacent to the fire. This obscuration normally occurs when a fire is burning in the bottom of a drainage and the smoke is trapped by a temperature inversion. Over such sites the pilot can usually aline the aircraft with the fire by using reference points visible outside the smoked-in area. When he must fly over a particular portion of the fire, some secondary means of navigation may be needed.

At large fires, the smoke pall may cover several hundred square miles. This condition was encountered in 1964 at the Coyote Fire near Santa Barbara, California; in 1965 in the multiple-fire situations in West Virginia and Nevada; and in 1966 at the Oxbow Fire near Eugene, Oregon. Under these conditions, the pilot must use radio navigational aids in alining the aircraft.

In many areas in the Western United States, where wildland fires are a problem, the distance to standard radio navigation facilities (OMNI, DME) is too great for them to be used for accurate navigation. Under these circumstances, systems such as Doppler radar or other inertial devices should be provided. An adequate navigation system in combination with a real-time IR viewer can provide the capability for alining the aircraft with portions of the fire that are especially important. If a real-time display of the IR imagery is available, the problem of determining the position of the aircraft with respect to the fire front is greatly simplified, and the time required to obtain adequate coverage is minimal. Unfortunately, the performance characteristics of available real-time viewers leave much to be desired in luminosity and resolution; their performance is marginal at best.

ALTITUDE SELECTION

The altitude selected for the initial surveillance flight should be high enough to permit coverage of the entire fire width on one pass, with adequate allowance for navigation errors. If the scale of the imagery produced at this altitude is inadequate to provide the detailed information needed on portions of the fire, subsequent passes can be flown at lower altitudes. Selection of altitude for followup missions must be a compromise based on resolution requirements, number of passes to complete the data gathering, navigational errors, and adequate terrain clearance for safe operations.

GROUNDSPEED

Groundspeed of the aircraft must be determined accurately prior to the beginning of a pass. If a Doppler radar is available, this information is obtained quite easily. If not, the pilot can use standard navigational procedures to determine his expected groundspeed over the target. Groundspeed information is needed to adjust the printer V/H for correct aspect ratio on the imagery. Unless an accurate groundspeed measurement is available, passes must be made in opposite directions or in two directions at right angles to each other over the fire. Imagery thus made readily reveals any errors in V/H setting (fig. 13).

FLIGHT SCHEDULING

The prime consideration in scheduling IR fire-mapping flights is to provide the fire staff with current information in time to assist in formulating attack plans for the next shift. Usually, during the uncontrolled stage of the fire the desirable flight times are 0400, 1000, 1400 to 1600, and 2000 to 2200 hours. Scheduling must allow for the unavoidable time lapse between collection of

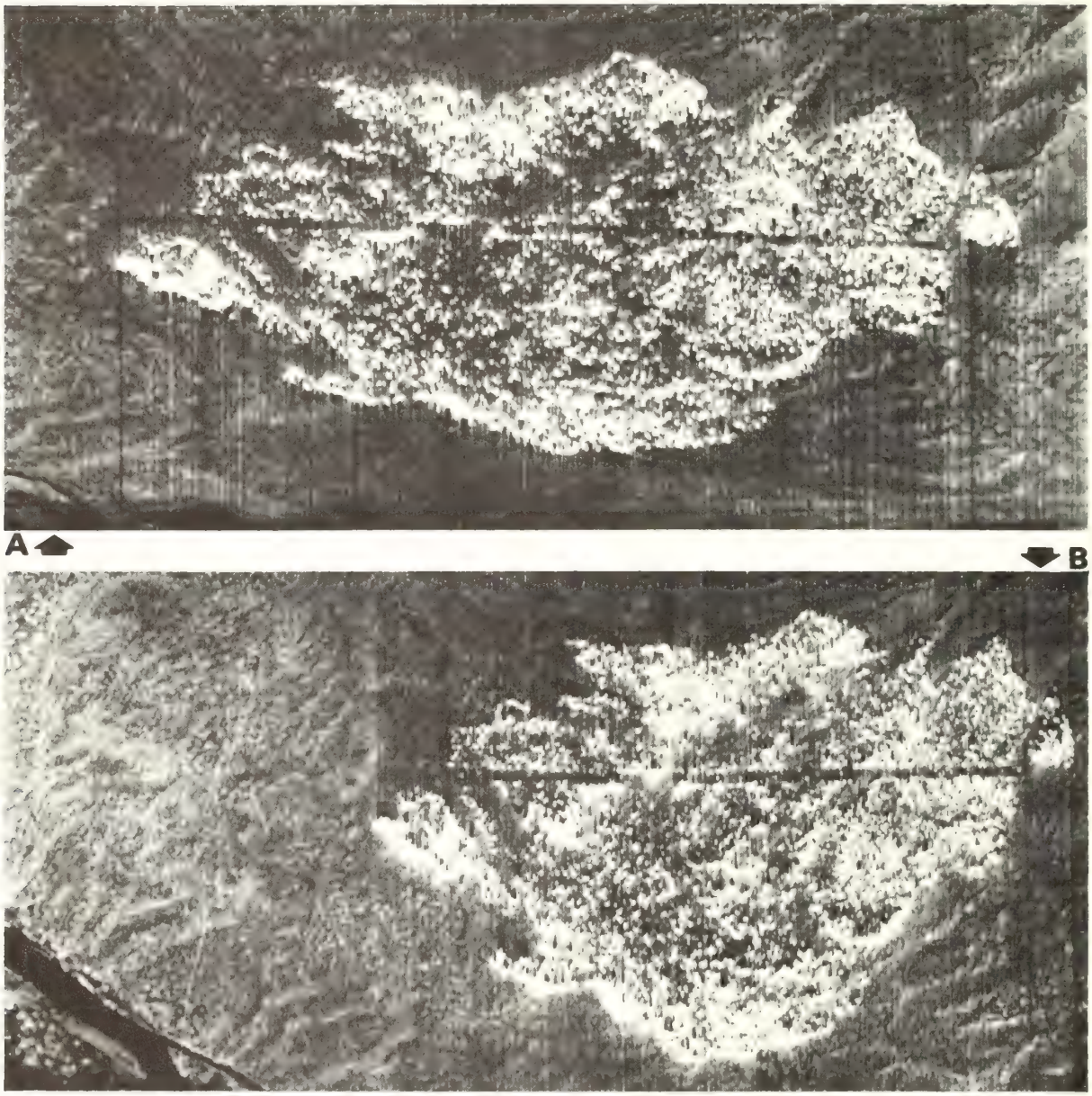

Figure 13.—Improper V/H adjustments cause: A, elongation; B, compression of fire area on IR imagery.

imagery and delivery of interpreted intelligence to the fire camp. The hours immediately before and after sunrise and sunset should be avoided since thermal washout, low sun angle, and rapidly changing conditions make it extremely difficult to obtain good terrain detail on IR imagery. Once a fire has been contained, it is the consensus that two flights per day should provide adequate intelligence. Flight schedules for these missions would be determined by fire staff.

DELIVERY OF IMAGERY

Imagery has no operational value until it is delivered to the fire camp and interpreted. Two methods of delivery used throughout this program were (1) airdrop from the scanning aircraft, and (2) delivery by ground transportation from the nearest airport. These methods do not require complex, expensive telemetering ground stations at the fire camp. Airdrop is simple and fast, but it

has several serious limitations. It is difficult to find a suitable drop zone if the area adjacent to the fire camp is obscured by smoke. Quite often, traffic of helicopters and aircraft dropping retardant in the vicinity of the fire camp causes serious delays. Airdrop involves some risk when the fire camp is located in a canyon bottom. However, delivering the imagery from the nearest airport is sometimes subject to intolerable delay.

Fire intelligence is frequently needed at both the main fire camp and at zone camps around the fire perimeter. A telemetering system for instantaneous transmission of imagery to several locations simultaneously would have great operational value.

1963 AND 1964 FIELD SEASONS[8]

TRAINING AND FIELD TESTING

The modified AAS/5 scanner, with a single Polaroid camera, was used on 65 fire-mapping flights in the 1963 and 1964 fire seasons (table 2). More than 800 pieces of imagery were produced over a wide variety of fuel types and burning conditions. Table 5 (appendix V) analyzes operational performance for individual missions during the 1964 fire season. In addition to operational missions, more than 80 training missions were flown to test equipment and develop proficiency of the crew.

PERIMETER INTELLIGENCE

IR imagery was used to determine location of the perimeter of 10 uncontrolled wildfires; on seven of these fires it would have been impossible to map the fire perimeter accurately using conventional reconnaissance. On three of the 10 fires, IR was the sole source of fire perimeter information. IR reconnaissance became an integral part of the strategic and tactical fire control planning.

The quality of the IR imagery varied widely. Equipment failure prevented collection of usable imagery over one fire. Even with poor quality imagery, we plotted the fire perimeter accurately enough to meet the minimum requirements for large fire strategic and tactical control planning.

INTENSITY INTELLIGENCE

Fire imagery graphically portrays the relative heat intensity of burning forest fuels (figs. 14 and 15). On 13 of the fires mapped in 1963-64, this intensity intelligence was shown to command personnel and always proved to be valuable in deploying air and ground forces to suppress priority hotspots along the perimeter. The Candle Mountain Fire on the Helena National Forest (Northern Region) demonstrated the value of IR intensity intelligence; this fire had started from lightning in a roadless, subalpine timber stand of spruce, fir, and lodgepole. Although fire spread was stopped at 1700 hours on July 23, a comparison of imagery obtained at 2200 hours on July 23 with that obtained at 0530 hours on July 24 showed little change in intensity during the intervening hours of darkness (figs. 16 and 17).

Visual reconnaissance made at daylight on July 24 showed very little smoke rising from the burned area. This information ordinarily would have suggested releasing manpower, particularly since the fire perimeter had not increased during a 12-hour period of cooler temperatures and higher humidity. But the intensity intelligence obtained from the IR convinced command personnel not to release line workers during the day shift and to pursue vigorous mopup.

SPOT FIRE INTELLIGENCE

Spot fires were encountered on three of the fires mapped. On two of them, spotting

[8] *The 1965 activities are reported under PROTOTYPE FIRE-MAPPING SYSTEM.*

Table 2.—Wildfire-mapping missions for Project Fire Scan test program, 1963-64

Year	Fires	Flights		Average fire size	Imagery drops	Fires using IR intelligence	Fuel types encountered
		Day	Night				
				Acres			
1963	7	15	1	11,300	8	3	Fir-spruce Grass Pine Sagebrush
1964	16	33	16	19,800	19	12	Pine Fir-spruce Oak-brush Grass Sagebrush

was not a major threat; but on the third, one of three spot fires had not been detected by ground forces (fig. 18). During the mapping mission, location of the undetected spot fire was radioed to suppression forces, and they were able to take control action before it became serious. On each of these three fires, IR imagery clearly revealed the presence of spot fires. Smoke often prevents early detection of spot fires by visual reconnaissance.

MOPUP

Mapping of aboveground burning fuels was performed on 11 wildfires during mopup.

Figure 14.—IR imagery of Nuns Canyon Fire, 1964.

Figure 15.—IR imagery of Coyote Fire, 1964.

Figure 16.—IR imagery of Candle Mountain Fire, 2200 hours on July 23, 1964.

Figure 17.—IR imagery of Candle Mountain Fire, 0530 hours on July 24, 1964.

IR imagery obtained during mopup of these fires was valuable in planning tactical employment of manpower and equipment. Figure 19 shows hotspots on approximately 6½ miles of cold fire perimeter. This imagery enabled control officers to deploy forces to portions of the perimeter where burning fuels still persisted.

At this stage, burning fuels often are hot coals that give off too little smoke to aid in visual detection. These hot coals are a source of firebrands that could be windborne into unburned fuels outside the perimeter. Detection of hotspots by conventional visual means on large fires like the Coyote Fire (more than 70 miles of perimeter) requires very large expenditure of manpower. IR mapping reduces this problem.

INTERPRETATION

An average of 40 minutes was required to transfer fire intelligence from IR imagery to aerial photos and/or maps. Interpretation time, plus an average of 1 hour for each flight, resulted in an average of 1 hour and 40 minutes from the first imagery run over a fire to delivery of the completed map.

On most fires, intelligence was transferred from the imagery to aerial photos and finally to topographic or planimetric base maps. This method uses corresponding grids for transferring imagery of the fire perimeter to its appropriate location on a photo and finally to a map. The grid method worked well for areas where there were no radical changes in vegetative type or manmade features.

Figure 18.—IR imagery of Crazy Creek Fire, 1964.

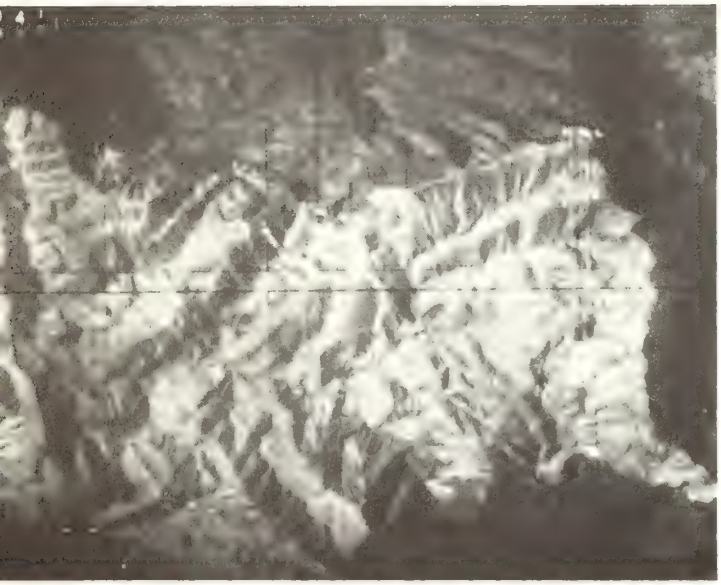

Figure 19.—IR imagery of Coyote Fire, 1964, during mopup.

On three fires there were enough recognizable landmarks to eliminate need for the intermediate step, i.e., use of a photo. This method was simpler and quicker but could be used only where numerous changes in vegetative types are found or where there are recognizable manmade features such as logging roads, clearcut logging units, orchards, or rural and suburban habitation (fig. 20).

Figure 20.—IR imagery of manmade features adjacent to the Mill Creek Fire, 1964: A, Orchard; B, road.

Imagery obtained during the first 2 hours after sunrise and the 2 hours before sunset was difficult to interpret because the scanner operator could not compensate for rapid changes in thermal contrast. Early morning sun on south slopes obscures portions of the fire perimeter, but terrain features on contrasting north slopes are difficult to distinguish (figs. 21 and 22). When equip-

Figure 21.—Degradation of IR imagery by the early morning sun, Big Creek Fire, 1964.

Figure 22.—Degradation of IR imagery by the early morning sun, Willow Tree Fire, 1964.

ment settings are made to accommodate south slope conditions, they usually produce an adverse contrast on north slopes (or vice versa).

DROPPING IMAGERY

On seven fires we used special equipment (figs. 23, 24, and 25) to drop imagery to the ground interpreter. Airdropping is cheap and effective. We made 21 daytime and 7 nighttime drops, all of which were successfully retrieved. Our training and operational missions showed that drops could be consistently placed within a clearing 500 feet in diameter. The average day drop was made at 200 feet over terrain and the average night drop at 500 feet.

FIRE COMMAND INTERVIEWS

During the winter of 1964, supervisory fire control personnel from the six western Regions of the Forest Service were interviewed to obtain a consensus of needs for intelligence on large fires. Information gathered in these interviews was to be used in planning operations for the transition of IR mapping from experimental to operational status. It was hoped that these interviews would provide criteria for specifying requirements for optimum design.

Responses from supervisory personnel.—We interviewed Forest Supervisors, District Rangers, and other Forest staff personnel who had been responsible for directing control operations. These men all wanted to obtain early intelligence about perimeter locations, rate of spread, spot fires, fire intensity, and location of interior unburned or scorched areas. They strongly emphasized the need for early receipt of information about intensity of fires and delineation of unburned areas.

These fire control supervisors preferred working from maps and aerial photos rather than directly from the IR images for portraying intelligence at command headquarters and for tactical line overhead use.

Figure 23.—Side view of drop tube ejector assembly.

Figure 24.—Ejector assembly with drop tube fully inserted.

They showed that appearance of dozer-built control lines on fire imagery was highly important to them, whereas location of handlines and pumper units was less important. Average desired frequency for obtaining intelligence about perimeters was five times per day during the uncontrolled stage and twice daily during the controlled (mopup) stage. Preferred time of day for receiving such intelligence coincided with planning sectors for changing shifts and for obtaining "heat of the day" intelligence. Most interviewees felt the fire boss and plans chief should physically view the fire at least twice daily.

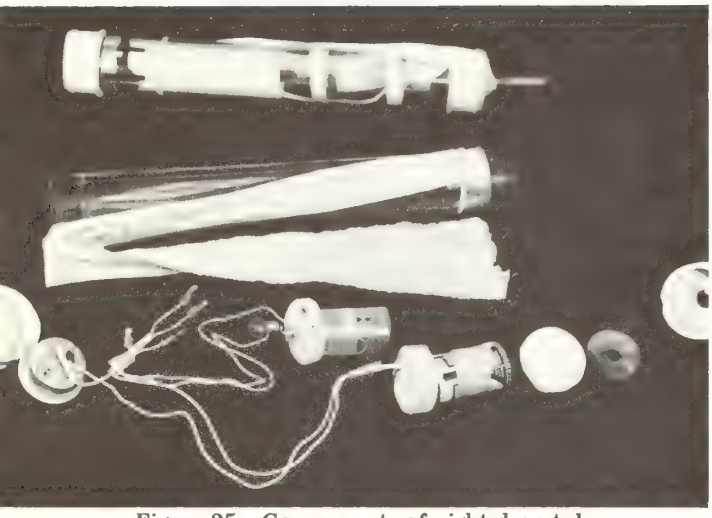

Figure 25.—Components of night drop tube.

Responses from overhead personnel.—We recorded on-the-scene comments by fire bosses and other supervisory personnel during the mapping operations in 1964. While capturing their spontaneous reaction to our pioneer mapping effort, we made useful data available to them to improve their operating techniques and to support continuation of the mapping program. Comments from fire bosses showed that IR maps gave them early accurate information about perimeter and hotspot locations, whereas intelligence from conventional sources was either lacking or was available too late to be useful. IR prints available in early stages of large fires may have obviated need for requests for additional men and allowed shifting of existing forces for most efficient use on the fireline.

These men expressed need for having imagery dropped directly to zone headquarters since IR intelligence does not filter down from GHQ during fluid stages of the fire when flanks are spreading faster than suppression forces can cope with them. A larger format (9 by 9 inches), with smaller scale imagery, was believed to be more useful than standard Polaroid prints in presenting the "big picture" to command overhead.

RESULTS OF THE 1966 SEASON

The Reconofax XI fire-mapping system was operated successfully throughout the 1966 fire season. Twenty-one flights over 15 fires, plus five training missions, were flown to evaluate the system's operational capabilities.

Dropping the Polaroid imagery to fire camp was an acceptable method of delivering the fire intelligence. However, smoke, haze, darkness, and other aircraft sometimes limit the usefulness of airdrop delivery. Aircraft weight restrictions and cost of telemetering systems precluded their use in the fire-mapping prototype.

A side-by-side comparison (fig. 26) of 70-mm. and Polaroid fire imagery (the images are of two passes over the same fire) reveals several problems:

1. The black lines across the film (at the same place on both images) are caused by fires outside the 120° field of view (see p. 15).

2. Accurate adjustment of V/H is difficult over wild, unknown terrain (note the compression of the river in the Polaroid image).

3. Some fire images have fuzzy or poorly defined boundaries (e.g., the left side of the fire near the center) which we have not yet successfully explained. They may have been caused by flames over the adjacent terrain, hot gases or particles ahead of the fire, or heating of the materials ahead of the hot area.

Figure 27 shows the complete fire (fig. 26) within the 120° field of view and the black lines are missing.

Operational testing in 1966 revealed changes that should be made to the system:

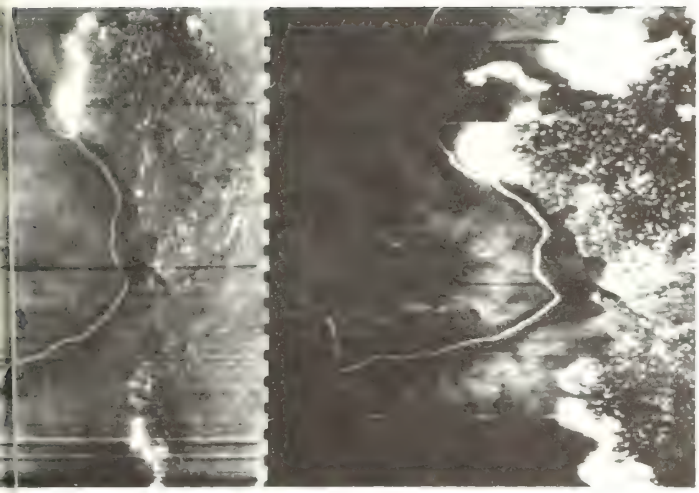

Figure 26.—Composite photograph comparing 70-mm. and Polaroid fire imagery.

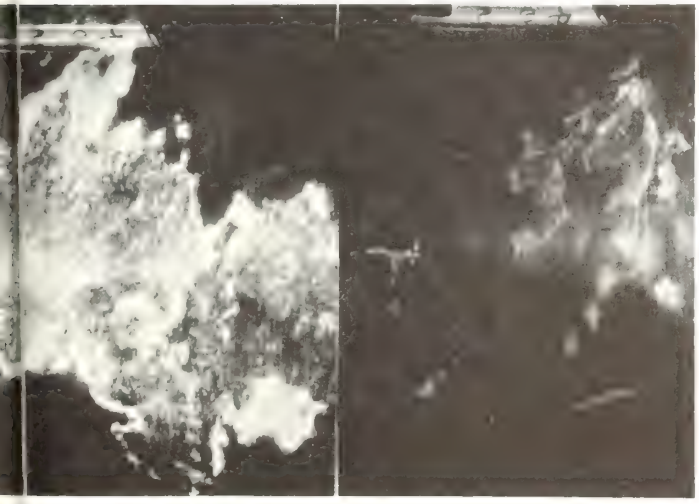

Figure 27.—Polaroid pictures of sequential imagery of the total fire shown in figure 26.

1. Replacement of the viewer high-voltage power supply with a heavy external unit was required after two failures of the internal power supply. A new power supply should be selected to reduce weight and ripple and to permit high altitude operation.

2. A new power supply is required to provide adequate focus voltage for the viewer CRT to insure a sharp electronic focus.

3. The frame counter in the camera slating unit counts each vertical sweep of the viewer. Sequential numbering of the Polaroid prints could be obtained if the counter were connected in series with the shutter-flash switch.

4. The d.c. restoration should be corrected to eliminate the shift in film intensity caused by fires outside the 120° field of view. Increasing the scanner dead time, reducing the d.c.-restoration clamp time, or vignetting the receiving aperture are possible solutions.

5. Amplifiers in the viewer and monitor are a.c. coupled without d.c. restoration and are severely upset by intense signals. D. c. restoration should be included in all a.c.-coupled video amplifiers.

6. A better 70-mm. film drive is required to prevent film striations, which make interpretation difficult, if not impossible.

OCCURRENCE OF LARGE FIRES

The consensus of fire control experts in various parts of the country was that in the West (U.S. Forest Service Regions 1 through 6), where fuel types are highly combustible and weather conditions frequently produce extreme fire danger, any fire burning over 100 acres (Class D and larger) could effectively use IR fire mapping. By contrast, in the Eastern United States (U.S. Forest Service Regions 8 and 9), where fuel types and weather conditions are less hazardous, no fire would need IR fire mapping until it reached 300 acres (Class E or larger).

We analyzed fire statistics gathered by the U.S. Forest Service (USFS Form 5100-29) through the 20-year period from 1944 to 1963 to determine the expected annual workload for an IR fire-mapping unit. Records of large fires in all Forest Service Regions are summarized for convenient reference (table 4, appendix V). From these

records, it appears that an annual average of 156 large fires (fig. 28) would require IR mapping. Average frequency of occurrence of large fires by 15-day periods is shown in figures 29 and 30. Figure 31 shows geographic distribution of large fires within peak fire seasons.

Peak fire seasons in western National Forests extend from May 15 to September 30, with overlap between geographic regions. By contrast, the peak seasons for eastern [9]

[9] *U.S. Forest Service Region 7 was combined with Region 9 in 1965.*

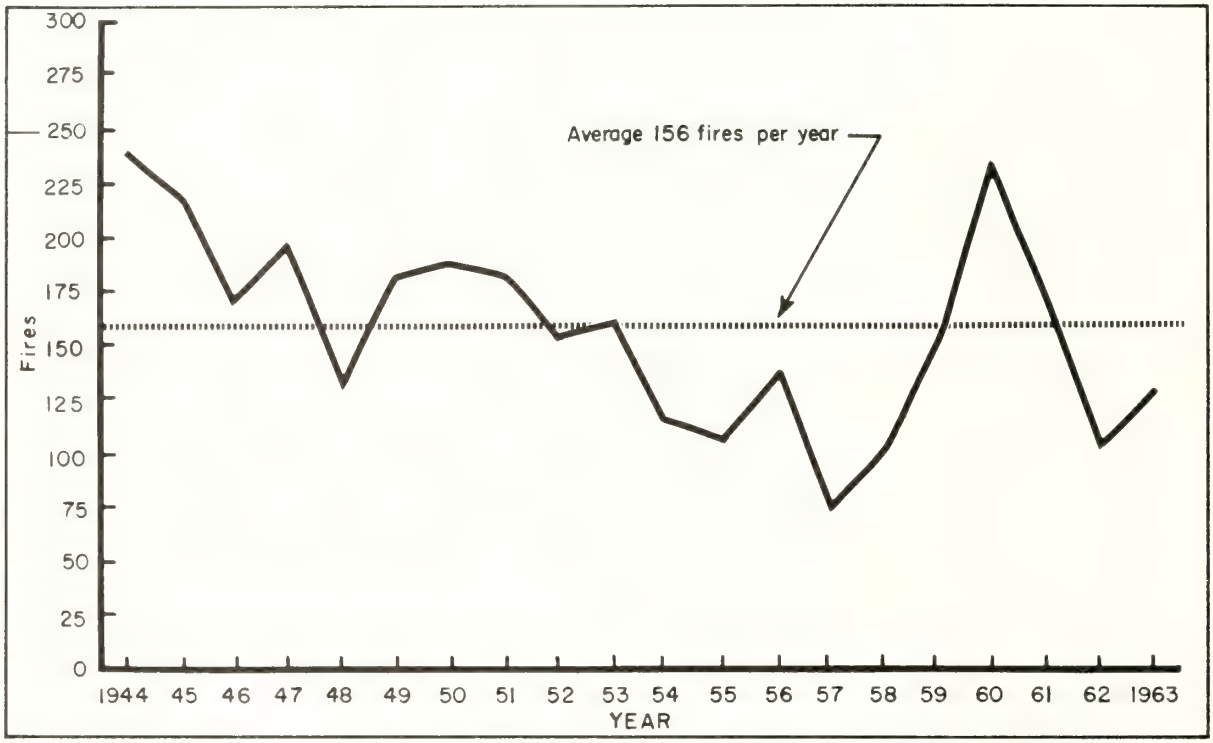

Figure 28.—Occurrence of large fires, U.S. Forest Service Regions 1 through 9, 1944-1963.

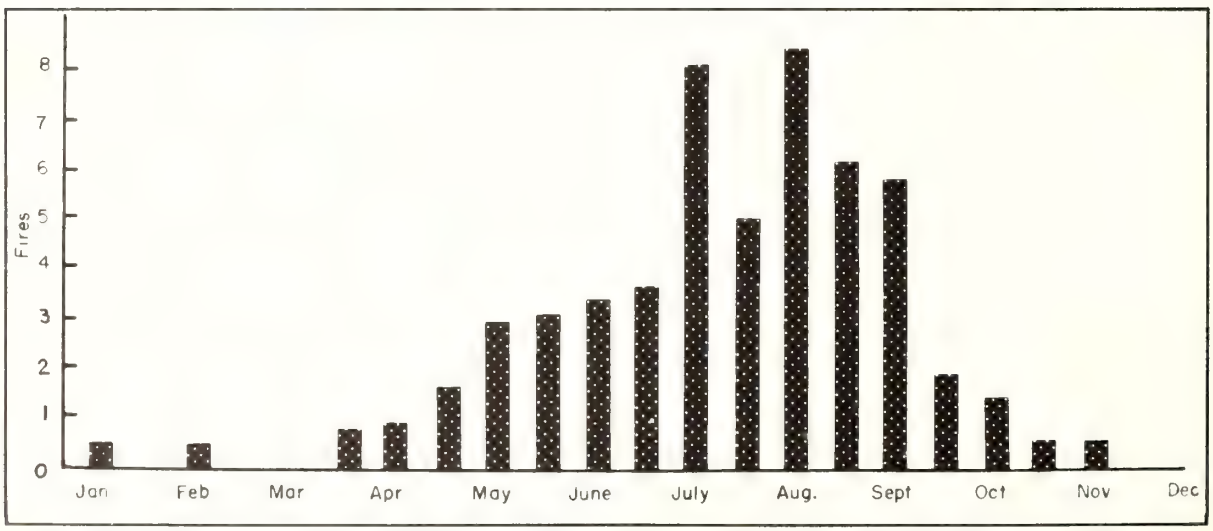

Figure 29.—Occurrence of fires 100 acres and larger in western U.S. Forest Service Regions 1 through 6, 1944-1963.

U. S. FOREST SERVICE
RESEARCH PAPER INT-49,1968

PROJECT FIRE SCAN
FIRE MAPPING FINAL REPORT

April 1962 to December 1966

(Work Unit 2521A)

SUMMARY

An IR scanner operated by U. S. Forest Service personnel consistently and reliably provided fire intelligence when visual surveillance was ineffective. IR imagery of uncontrolled wildfires provided much useful information about the location and extent of the fire perimeter, the existence and location of spot fires outside the main fire perimeter, and the relative intensity along various portions of the fire front. During the mopup and final control operations, this imagery was extremely valuable for locating lingering hotspots. IR intelligence enabled fire control officers to use their suppression forces most effectively.

During the 1964 fire season, 800 pieces of fire imagery were produced over 23 wild and 15 prescribed fires ranging in size from 10 acres to 215,000 acres. Many of these fires were obscured by dense smoke palls, but smoke caused no degradation of image quality.

In 1966, a prototype IR scanner using a liquid nitrogen-cooled InSb detector, an internal 70-mm. crater lamp recorder, and an external cathode ray tube recorder equipped with a dual Polaroid camera was evaluated and found to be satisfactory for use in operational fire-mapping missions.

U. S. Forest Service records of large fires during the period 1944 through 1963 showed an annual average of 156 fires large enough for advantageous use of IR surveillance. Since fire occurrence follows seasonal patterns that differ widely from one part of the country to another, it should be possible to use IR equipment effectively by shifting scanners regionally as the fire season progresses.

Fire control officers have accepted IR mapping enthusiastically. Decisions based on IR intelligence often resulted in a reduction in fire suppression costs. No quantitative cost analysis of infrared fire mapping was made; until such a study is done, no meaningful cost effectiveness predictions are possible.

Hirsch, Stanley N., Robert L. Bjornsen, Forrest H. Madden, and Ralph A. Wilson.

1968. Project Fire Scan fire mapping final report April 1962 to December 1966. U.S. Dep. Agr., Forest Serv., Intermountain Forest and Range Exp. Sta., Ogden, Utah 84401. 49 pp., illus. (U.S. Forest Serv. Res. Pap. INT-49)

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National Forests occur in early spring and late fall. "Peak season" is arbitrarily defined as the period when one or more large fires burn during a given 15-day period.

Data summarized in this section should provide the information necessary to determine how many IR scanners are required to meet the U.S. Forest Service's annual expected fire load. Since the actual number of units required would depend strongly on operational procedures, we felt it was beyond the scope of this report to recommend the number of units to be acquired.

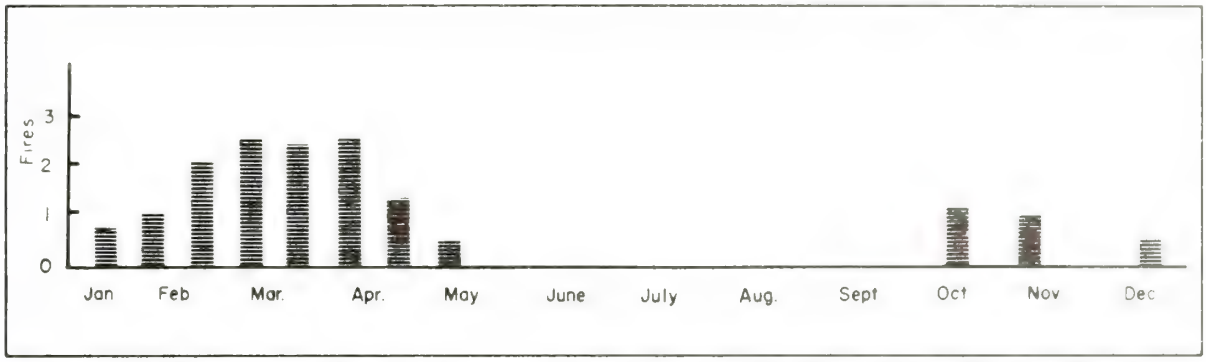

Figure 30.—Occurrence of fires 300 acres and larger in eastern U.S. Forest Service Regions 8 and 9, 1944-1963.

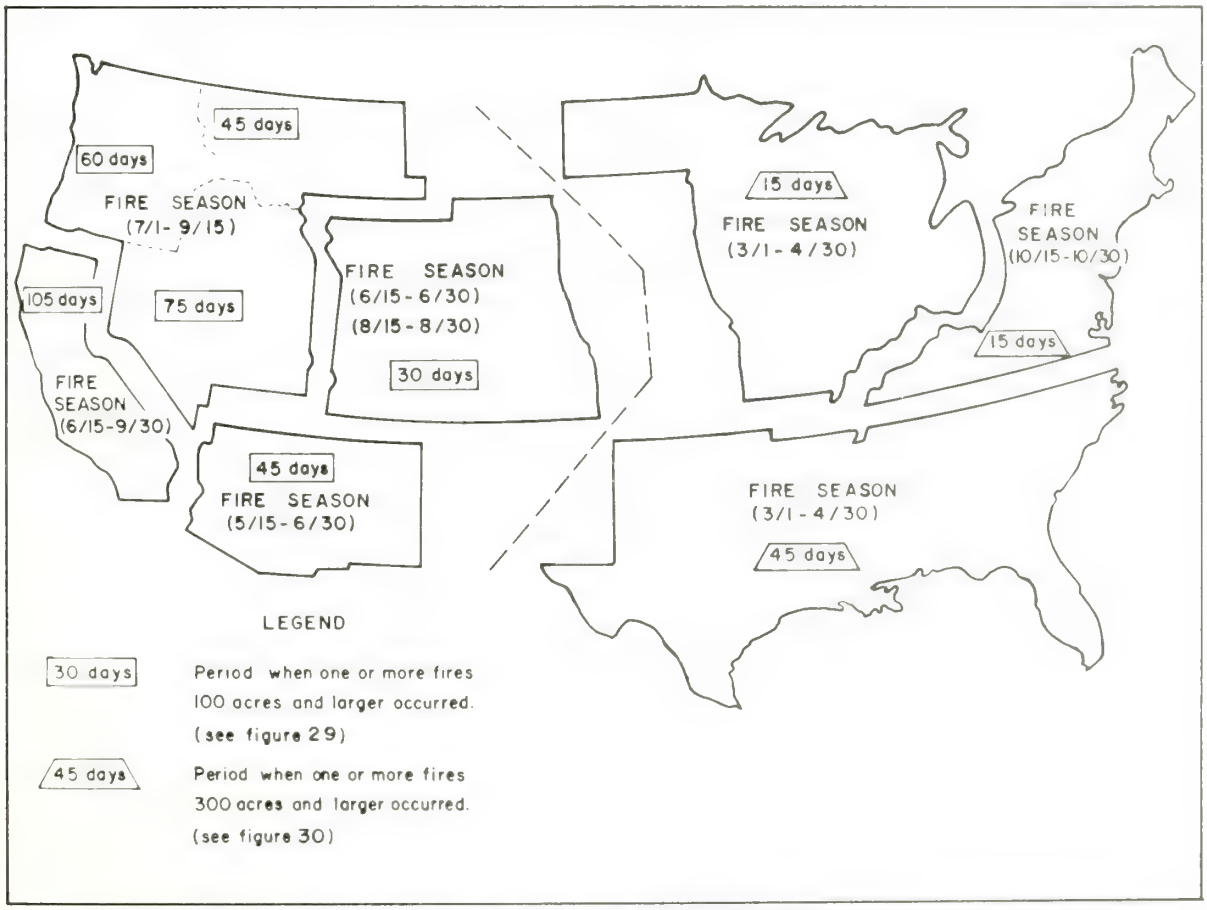

Figure 31.—Average number of days per year when large wildfires have occurred, 1944-1963.

Table 3.—Summary of Class D and E fires[1] in National Forests, 1944-1963

Forest Service Region	Average number	Average duration	Total Days to control and mopup	Average size
		Days		Acres
1	11.4	10.0	114	620
2	8.6	5.8	50	410
3	18.1	7.4	133	290
4	25.5	4.7	120	1,550
5	50.0	5.8	290	1,750
6	17.7	10.1	189	260
7	2.6	6.5	17	2,500
8	17.1	2.8	48	550
9	5.3	2.1	11	1,060

[1] *Fires 100 acres and larger in Regions 1 through 6: 300 acres and larger in Regions 7 through 9.*

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APPENDIX I

FOREST SERVICE—U. S. DEPARTMENT OF AGRICULTURE

Intermountain Forest and Range Experiment Station
Northern Forest Fire Laboratory
Missoula, Montana

January 29, 1964

DESIGN CRITERIA FOR A PROTOTYPE AIRBORNE INFRARED FIRE SURVEILLANCE SET

INTRODUCTION

An experimental program has been conducted by the U.S. Forest Service in cooperation with the Office of Divil Defense to determine whether airborne infrared line scanners can provide surveillance information on fires of one-tenth acre to several thousand acres in size when smoke or darkness prohibits the colleciton of this information by other means. After 2 years of flight tests with a modified military scanner, results indicate the desirability of developing a prototype scanner specifically designed to meet the requirements of forest fire and civil defense applications. This specification outlines the general requirements for a prototype fire-mapping scanner to be installed and operated in a light twin-engine aircraft.

OPERATION

The equipment shall be designed to be operated by personnel with no previous electronic training. Equipment operators will be selected from forestry and civilian defense personnel with at least a high school education and above-average alertness and dexterity.

The equipment will be operated in light twin-engine aircraft at altitudes from 2,000 to 15,000 feet above terrain and at airspeeds from 100 to 180 knots. Under these conditions the equipment must be capable of producing high quality imagery of terrain, fire perimeter, and small spot fires, with sufficient detail so that a skilled infrared imagery interpreter can precisely determine the location of the fire perimeter with respect to terrain and manmade features such as roads, bulldozer constructed firelines, etc.

The output of the scanner shall be displayed on a B-scan monitor suitable for assisting the pilot in positioning the aircraft over the fire area. The scanner must be capable of recording terrain detail along the perimeter of extremely hot fires.

PERFORMANCE REQUIREMENTS

Scan angle.—120°

Roll stabilization.—±10°

Angular resolution.—Optical system resolution shall be as high as is obtainable with state-of-the-art equipment. A 1-milliradian system resolution capability is desirable. A 2-milliradian system resolution capability is the minimum acceptable.

Temperature resolution.—2° C. maximum in the spectral region from 4.5 to 5.5 microns.

V/H.—0.13 per second maximum.

Dynamic range.—Dynamic range shall be adequate to handle the signal from hot fire targets without incurring saturation while the system gain is set for terrain mapping. Previous experiments have shown that a logarithmic attenuator with a 3-decade range is adequate for this function.

Display.—An A-scan monitor shall be provided to assist the operator in determining overall system performance.

A B-scan monitor shall be provided with provision for either 60° or 120° display angle.

Recording.—A Polaroid camera shall be provided to photograph the B-scan monitor. Any alternate proposal whereby processed positive imagery can be made available rapidly will be considered.

Provision for external recording.—Suitable connectors shall be installed to supply video, sync, and V/H signals to auxiliary recording and telemetering equipment.

Power requirements.—28 v. d.c., 30 amp. maximum.

Size and weight.—Size and weight shall be consistent with installation in the aircraft mentioned below while still permitting space and weight capabilities for a pilot and two scanner operators.

OTHER DESIGN CONSIDERATIONS

Installation.—This system shall be designed to permit installation in light twin-engine aircraft such as an Aero Commander, Cessna 310, Beechcraft G-50, etc., with a minimum amount of structural modification to the aircraft. Once the initial modification has been made, installation or removal of the equipment shall not require more than two men or more than 30 minutes' time.

Detector cooling.—The use of liquid gas for detector cooling is undesirable because of logistic difficulties. The elimination of the necessity for detector cooling would be the most desirable approach; however, since at present this does not appear feasible, the use of closed cycle coolers should be considered and the cost and complexity weighed against the undesirable characteristics of liquefied gases.

Maintenance.—The equipment will be maintained by forestry and civilian defense personnel skilled in normal electronic equipment maintenance. Wherever possible, modular construction shall be employed to permit in-field servicing by replacement. Solid state devices shall be used in place of vacuum tubes wherever system performance will not be jeopardized.

The equipment shall be designed to completely eliminate any need for precise optical adjustments in the field. In no case shall any specialized optical equipment be required for the maintenance of this device.

Future production.—This prototype scanner shall be designed to be compatible with production methods so that costs can be minimized in production quantities.

APPENDIX II

COPY COPY COPY

UNITED STATES GOVERNMENT
MEMORANDUM

Department of Agriculture-Forest Service
Washington, D.C. 20250

TO: Jack Barrows, Director
Division of Forest Fire Research

File No. 4400 (5100)

FROM: Merle S. Lowden, Director
Division of Fire Control

Date: December 1, 1965

SUBJECT: Forest Fire Research (Infrared Mapping)

Your reference:

As was suggested at our November 10 meeting, use of infrared imagery to map forest fires is at a stage of development where we should identify more specifically the information these techniques can record and furnish to the fire boss.

Infrared imagery provides the fire boss with a new tool to accurately map the fire edge under adverse conditions of smoke, smog, and darkness. This is progress, but knowledge of fire edge location alone is not adequate for effective fire control decision making. Effective decisions are also based on information concerning the dynamic characteristics of the fire perimeter and its relation to fuels, weather, topography, and values threatened. Thus, the mission of infrared fire mapping should be to furnish the above information, except weather, in sufficient detail to allow the fire boss to make informed decisions to control the fire. It will be necessary to capture this information more frequently, efficiently and economically than has been possible previously. In determining the degree of detail required of infrared imagery we must emphasize that under adverse conditions of smoke, smog, or darkness, infrared mapping presents the only obvious alternative means of gathering intelligence to laborious ground reconnaissance. The first and foremost requirement is a picture of the fire edge tied exactly to ground features. Ridge tops, valley bottoms, streams and prominent points should be discernible in sufficient detail to determine the precise location of fire edge, hot spots, spot fires, fuel type changes, and fuel breaks. In addition, the following degree of detail in infrared imagery is required for fire suppression decision-making when accompanied by maps showing topography, fuels, and physical features.

Fire Edge Characteristics—The following must be discernible:

1. The entire fire edge including smoldering edge, and flaming fronts.
2. Fire intensity and rates of spread on various sections of the fire.
3. Except under closed forest canopies, all constructed lines and natural breaks.
4. Spotfires outside the fire edge from smoldering to full flaming spotfires.
5. Size and location of spotfires.

Relationship of Fire Edge to Fuels—The following should be discernible:

1. Snags and hot spots burning inside the fire but within 300′ of the fire edge. It is desirable but not necessary to distinguish between snags and hot spots.
2. Unburned patches of fuel of more than 5 acres in size within the fire.
3. Major fuel type changes for a distance of one or more miles outside the edge of the fire, i.e.: Changes between grass and brush; timber and brush; conifer and hardwood; blowdown and standing timber; water and land; rocks and timber; rural and urban.

4. Fire breaks outside the edge of the fire, e.g. country roads, highways, streams not hidden by forest canopy, and prepared fire breaks.

Relationship of Fire Edge to Values Threatened

1. Structural improvements such as residences, bridges, factories, schools, and urban communities should be discernible.

Some of the foregoing details may seem demanding for existing or contemplated infrared mapping capability. Since these are the intelligence requirements for acceptable fire control, the objective should be to meet these demands as nearly as possible. Moreover, the capability to gather fire information in a single integrated reconnaissance operation would enhance fire control during a nuclear attack, especially in areas where detailed maps are unavailable.

/s/ Merle S. Lowden

APPENDIX III

DISTORTION

Familiarity with geometric distortions encountered in line scanning is essential to accurate interpretaion of imagery. The spectral sensitivity of the line scanner is determined by the detector and the filter used, but the geometric distortions are inherent in the scanner design and are independent of the spectral region selected.

Glow Tube Printer

Figure 32 is a schematic of a line scanner using a glow tube printer. A suitable detector is placed at the focal point of a parabolic mirror. The scanning function is performed by a flat mirror rotating at relatively high speed. Two microscope objectives are directly coupled to the scanning mirror shaft and oriented so that their axes are parallel to the path of the principal rays striking the scanning mirror. Energy from the terrain being scanned strikes the detector, and produces an electrical signal whose amplitude is proportional to the intensity of the incident energy. This signal is amplified and modulates the intensity of a glow tube with output in the visible spectrum. Light from the glow tube is deflected by a mirror, passed through the microscope objective and focused on panchromatic film. Direct coupling of the scanning mirror and the microscope objectives insures a direct correlation between the position of the spot focused on the film and the point on the ground producing the radiation incident on the detector. As the mirror rotates, a line is scanned across the ground perpendicular to the direction of the aircraft flight path, and a corresponding line is printed on the film by light from the microscope objective. The angular coverage displayed on the image is fixed by the geometry of the printer and the width of the film.

As the film is pulled past the microscope objective, a latent image of the terrain is formed. When the film velocity is directly proportional to the true groundspeed of the aircraft and inversely proportional to its height above ground, the image has proper aspect ratio. The position of the spot across the film is directly proportional to the angle between the scanning mirror and the nadir. The position along the film is proportional to true ground distance along the flight path.

Note that the position across the film is proportional to the angle and not to true ground distance, yet the position along the film is proportional to true ground distance. The result is an image having distortion similar to that encountered in normal photography in one direction, but with no distortion in the other direction.

To compensate for aircraft roll, a roll-stabilized recording magazine is used. As the aircraft rolls, the recording magazine is held level, and the angular correspondence between scanning mirror position and the nadir is maintained on the recording.

The glow tube printer has the advantages of simplicity and positive synchronization between the scanner and the printer. It has the disadvantage of being extremely difficult to rectilinearize.

Cathode Ray Tube Printer

The second method of recording line scan imagery uses a cathode ray tube (CRT) printer (fig. 33). The drive motor, scanning mirror, parabolic mirror, detector, video amplifier, and gyrostabilizer are identical to those used with the glow tube printer.

An electron beam sweeps across the face of a CRT. Magnetic pickups attached to the mirror synchronize the start of the sweep with the scanning mirror. Duration of the sweep is made equal to the time required for the scanning mirror to rotate through the desired display angle. The CRT's intensity is modulated by the amplified detector signal, and the trace is imaged on the film. As in operation of the glow tube printer, the film is

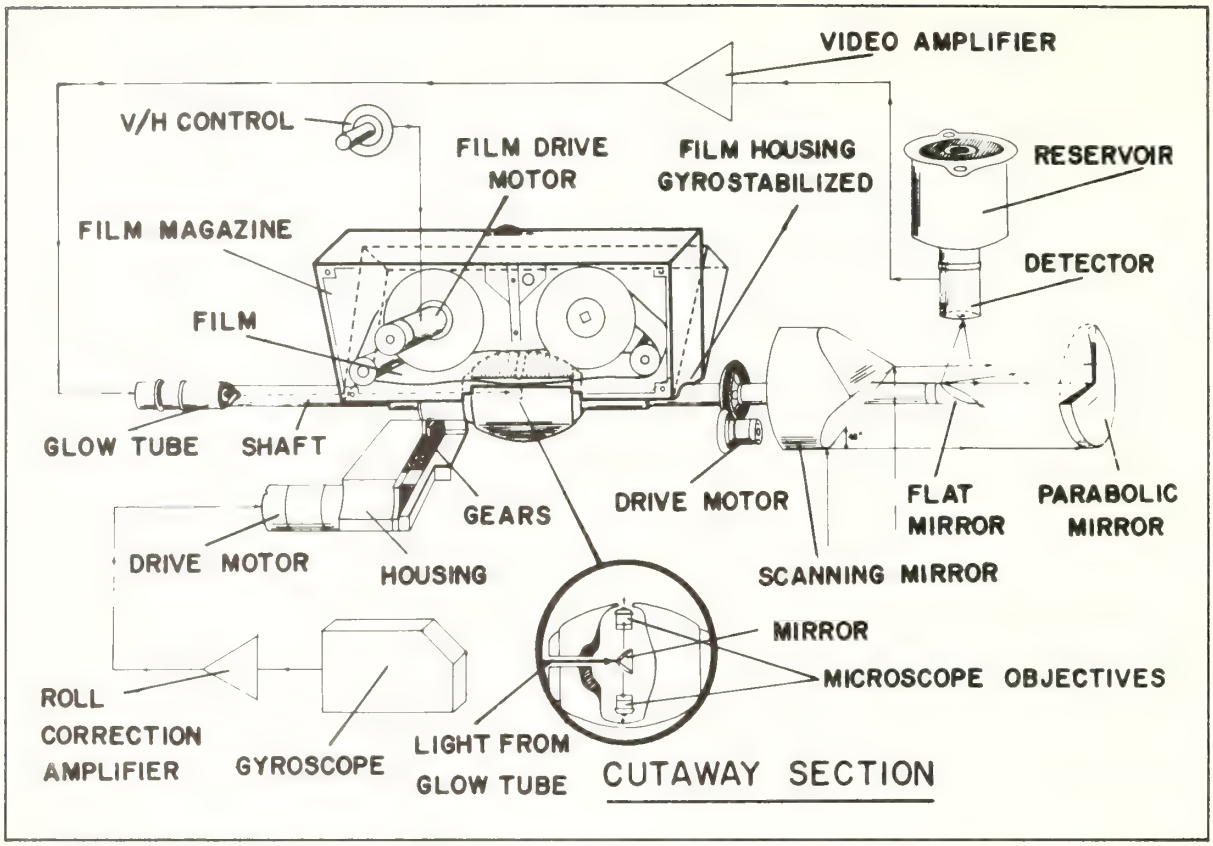

Figure 32.—Schematic of a line scanner using a glow tube printer.

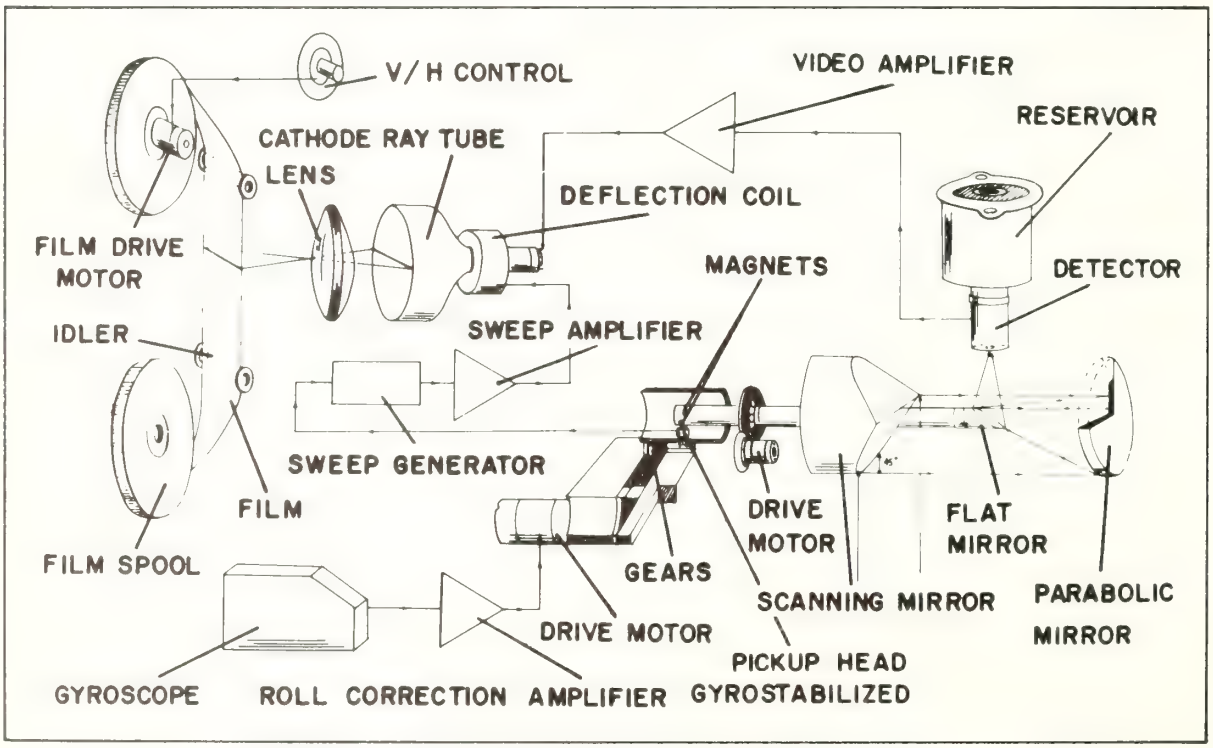

Figure 33.—Schematic of a line scanner using a CRT printer.

pulled past the scan line. Roll stabilization is achieved by varying the time at which the scan starts rather than by gyrostabilizing the recording magazine.

If the electron beam sweeps across the CRT linearly, the spot position on the film correlates directly with the angle between the scanning mirror and the nadir, and the same angular distortion is present that is in the glow tube printer. However, if the sweep is made nonlinear (rectilinearized) and, more specifically, if the sweep waveform is the tangent of the scan angle, then the position of the spot on the film corresponds to true ground position rather than to the scan angle. This gives true planimetric presentation.

The numerous disadvantages of the CRT printer are discussed in detail later in this section.

Resolution

Regardless of which printing method is used, the minimum resolvable spot size directly under the aircraft is determined by the focal length of the parabola, the size of the detector, the minimum spot size obtainable in the printer, and the height of the aircraft above the ground.[10] The maximum practically obtainable resolution is an order of magnitude poorer than conventional 1:15,840 aerial photography.

Distortions Inherent in Line Scanning

The size of the minimum resolvable elements at positions other than the nadir can be calculated as follows:

$$P = \beta \ h \sec \theta$$

and

$$F = \beta \ h \sec^2 \theta \qquad \text{(fig. 34).}$$

It is common practice to correct this imagery for roll, but not for pitch or yaw. If there is crosswind when the imagery is made, the aircraft heading and aircraft track do not coincide. Because of this, all points except those at the nadir are skewed in the direction of the aircraft crab (fig. 35). Any turns of the aircraft during the imagery run will cause straight roads parallel to the flight track to appear curved (fig. 36).

In practice, it is extremely difficult to determine true aircraft groundspeed and true height above terrain. Since these are not usually known accurately, the film velocity may not be correct, and the scale along the flight path will be different from the scale across the flight path.

Distortion Without Tangent Correction

If imagery is made without rectilinearization, the aspect ratio will be correct at the nadir or at two points equidistant from the nadir. Since the scale along the flight path is directly proportional to true ground distance, and the scale across the imagery is proportional to angle, it is impossible to maintain true aspect ratio throughout the image. A compromise is necessary and is usually made by selecting the film velocity so that true aspect ratio is maintained at either 30° or 45° from the nadir. This compromise results in minimum distortion over most of the image. If this aspect ratio distortion is ignored while attempting to perform even simple image interpretation, serious errors can result. A straight road crossing the flight path at an oblique angle will appear to be S-shaped (fig. 37).

Distortions Peculiar to CRT Printers

The CRT printer can be rectilinearized quite easily, but it has several serious disadvantages. The CRT printer is inherently more complex, but much more important to the imagery interpreter are distortions that result from electronic circuit drifts.

The angular coverage recorded on the image is determined by the angular velocity of the scanning mirror and the time duration of the sweep waveform used to deflect the CRT electron beam. It is easy to change the time

[10] *This assumes that the quality of the parabola and the flat mirrors is good enough to insure a blur circle much smaller than the size of the detector.*

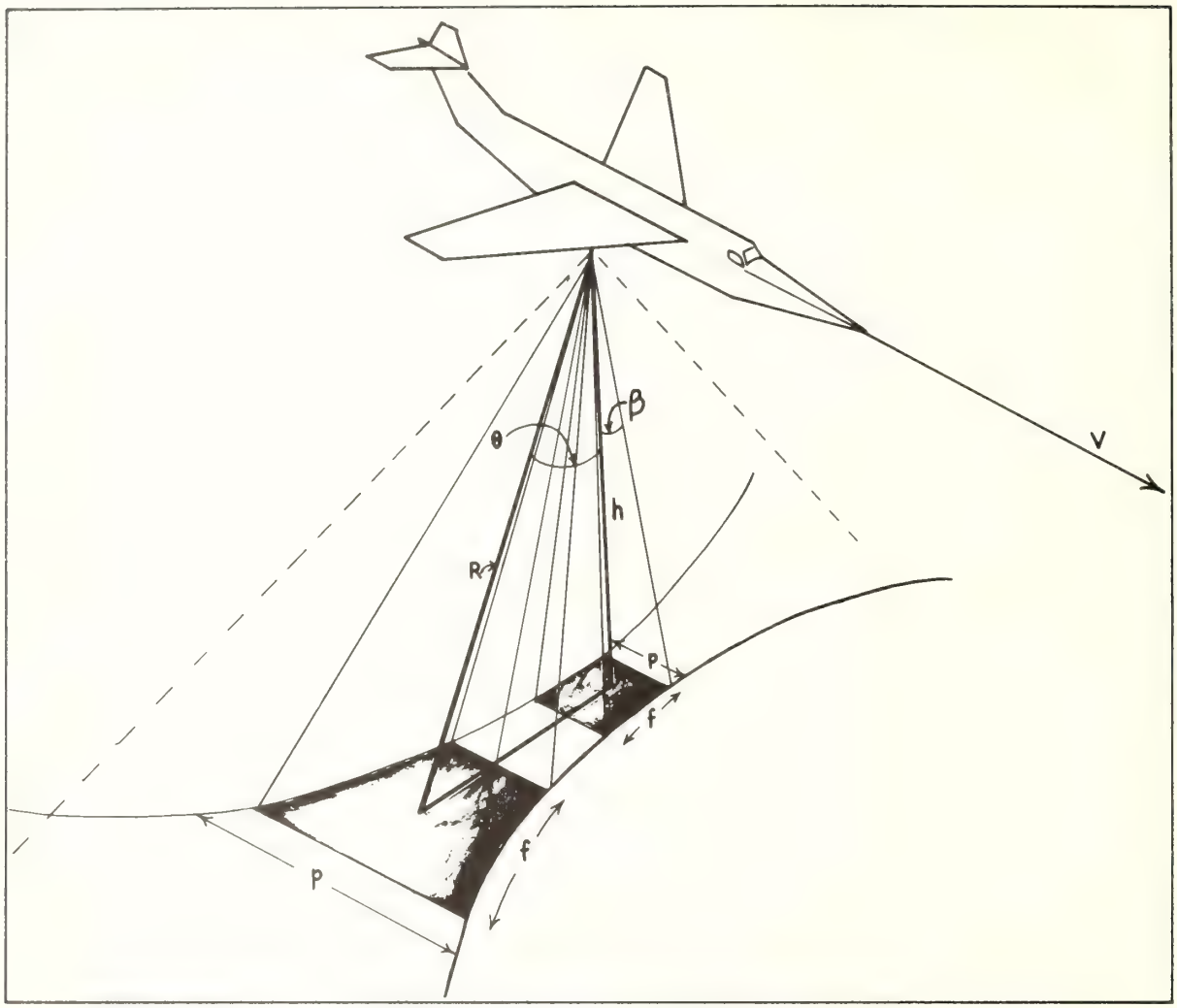

Figure 34.—Aircraft scanning geometry.

duration of the sweep to provide any desired angular coverage. This is worthwhile for providing versatility, but any drift in the electronics can easily result in an unintentional change in coverage angle. If careful checks are not made prior to image interpretation, these drifts can cause serious errors.

The ability to rectilinearize the imagery by developing a tangent sweep waveform is an asset of the CRT printer. But, again, drifts in electronic circuits result in a waveform that does not accurately follow the tangent curve, and unpredictable distortions may result. The tangent waveform required to rectilinearize the imagery results in nonlinear velocity of the electron beam across the face of the CRT. This nonlinear velocity produces a nonuniformity in brightness across the scan line. In order to produce usable imagery, this change in brightness must be corrected. If this correction is made exactly, no problem arises. Again, if electronic circuit drifts occur, this correction may be improper and serious shifts in tone across the imagery may result.

SUMMARY

Once we realize the number of ways in which angular and tonal distortions can be introduced into line scan imagery, we may wonder whether a device having so many inherent problems can produce any usable results.

Figure 35.—This rectilinearized image shows the effect of aircraft crab. Note that roads crossing the flight path do not form right angles with the road directly under the flight path.

Line scan technology will someday advance enough to produce truly stable equipment. In the meantime, we may use the wealth of information that line scanners can provide, but with care. IR imagery must always be checked against conventional photography so that distortion can be normalized. Landmark points must be transferred from imagery to aerial photos before making measurements.

Figure 36.—This run was made in the opposite direction to that shown in figure 35. Here the roads are skewed in the opposite direction. The apparent curvature in the road at the left side of the image was produced by turning the aircraft during the run.

Figure 37.—IR image showing distortion features.

APPENDIX IV

VIDEO ELECTRONICS FOR FIRE MAPPERS

The electronics in most thermal scanners are inadequate for mapping large forest fires. Signal processing that causes overshoot, ringing, and shift in signal level can aid in identifying low-energy targets. The same signal processing used with high-energy targets, such as forest fires, causes partial or complete loss of terrain detail near hotspots. Forest fire mapping requires electronic processing of variable amplitude and width signals without loss of detail of adjacent terrain. Amplifiers must have fast recovery, minimize overshoot, and retain the original terrain background reference level.

All systems of thermal imaging require signal amplification (or gain) to record small detected signals. Direct-coupled amplifiers are desirable for the application. But high-gain, direct-coupled amplifiers are inherently unstable and drift severely with temperature changes. Drift can be reduced by a.c. coupling, but a.c. coupling destroys the terrain reference required for fire mapping.

The problems with a.c. coupling can be investigated by studying the effects of terrain and fire signals (fig. 40) on the electronic transfer characteristic of an amplifier. A simplified a.c.-coupled amplifier with a synchronous clamp switch is shown in figure 38. The shape of the transfer characteristic (fig. 39) is very important to the results printed on film.

Assume a transfer curve with a linear portion (fig. 40). The typical input signal contains a series of maxima and minima corresponding to hot (maxima) and cold (minima) terrain temperatures (fig. 40A). Figures 40B through D show signals corresponding to fires of various energies and sizes superimposed on the terrain signals. Applying the signals from figure 40 to a capacitor removes the d.c. reference level. Terrain signals that were used to establish film gray

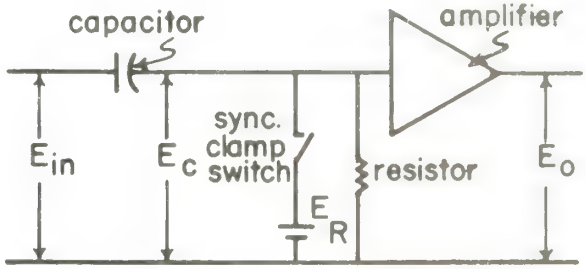

Figure 38.—A.c.-coupled amplifier.

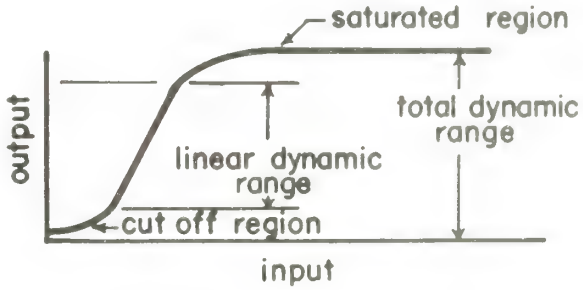

Figure 39.—Typical amplifier transfer curve.

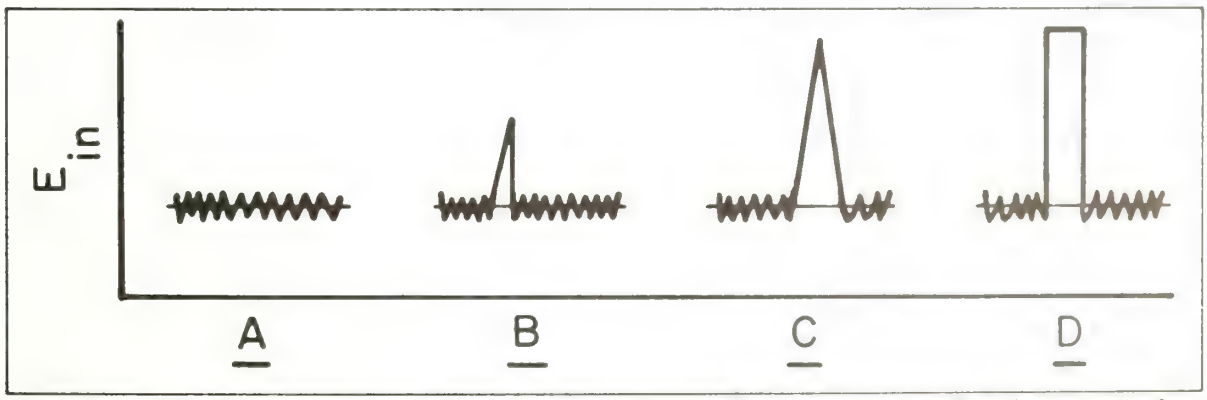

Figure 40.—Typical detector signals: A, Simulated terrain signal; B, with weak pulse; C, with stronger pulse; and D, with very strong signal.

scales are forced below the reference level by an amount equal to one-half the area under the fire signal (fig. 41). As the fire signal changes in height and width, the area under the curve changes, and the reference level is displaced up or down accordingly. The result is a continuing change in gray scales for the duration of the strong signals.

Returning to the transfer characteristics (fig. 39), we see that the linear region becomes the "linear dynamic range" of the amplifier. The total dynamic range, or the information available for printing on film, is the distance between the ordinates of the curve at cutoff and saturation.

Fire signals have a positive polarity with reference to terrain signals. The linear dynamic range of the amplifier can best be used by setting the bias point (Q-point) near cutoff (allowing for background fluctuations and temperature drift). Figure 42A shows a low-amplitude background signal amplified on the linear portion of a transfer curve. The average value of the input signal is zero, and the signal is amplified around the reference (or bias) point. Figure 42B shows a very narrow, high-amplitude pulse on the terrain background signal. The area under the pulse is small and does not change the reference level. Figures 42C through E show changes in background level produced by various pulse widths and heights. As the area under the pulse increases, the terrain signal reference is forced toward cutoff. Further increase in the pulse area causes the gain to reduce and produces a graying (reduced contrast) effect on the film. If the area is increased sufficiently to force the level beyond cutoff, the background signal is completely lost. Signals from forest fires exceed the cutoff limits.

When amplitude of the signal exceeds the transfer characteristic saturation point, further increase in the input signal does not change the output signal. The signal is said to be clipped or limited; hence, a voltage clipping circuit. The solution to loss of d.c. reference seems simple—clamp the terrain signals to a given reference and allow the strong signals to be clipped (fig. 42F). With an ideal restoration circuit, the reference level can be clamped and maintained for any fire signal. In reality, the restoration circuit becomes complicated. Signal amplitudes must be large enough to clamp before a.c. coupling can be used.

Restoration is accomplished by closing the synchronous clamp switch (fig. 38) and shorting the reference point to ground. (Any point other than ground may be selected by setting E_R to some reference level determined by the circuit requirements.) Selection of the reference time creates problems; fortunately,

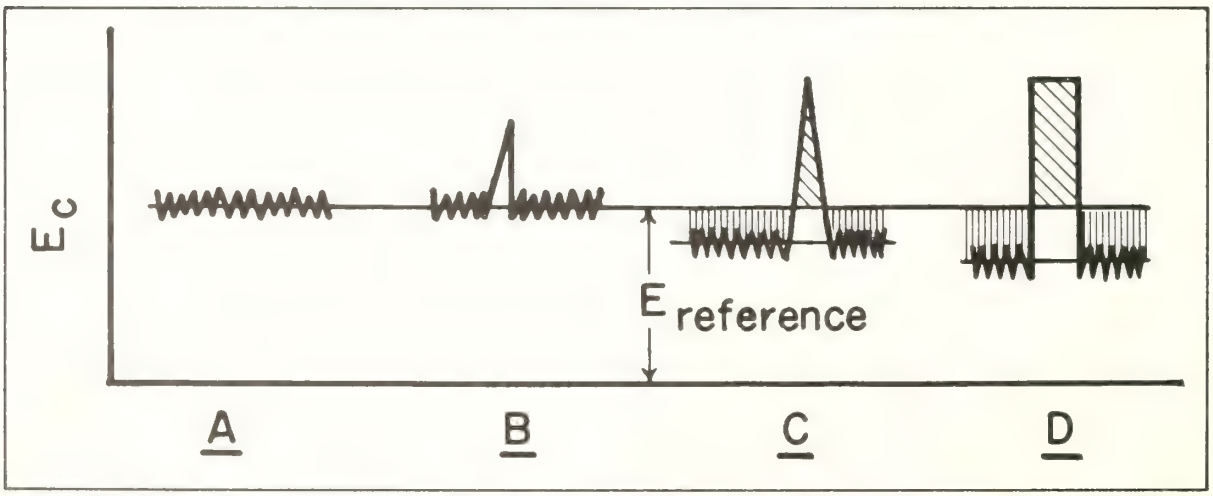

Figure 41.—Typical signal after a.c. coupling: A, Simulated terrain signal; B, no reference change with weak pulse; C and D, terrain baseline shifts from reference level as the signal area changes.

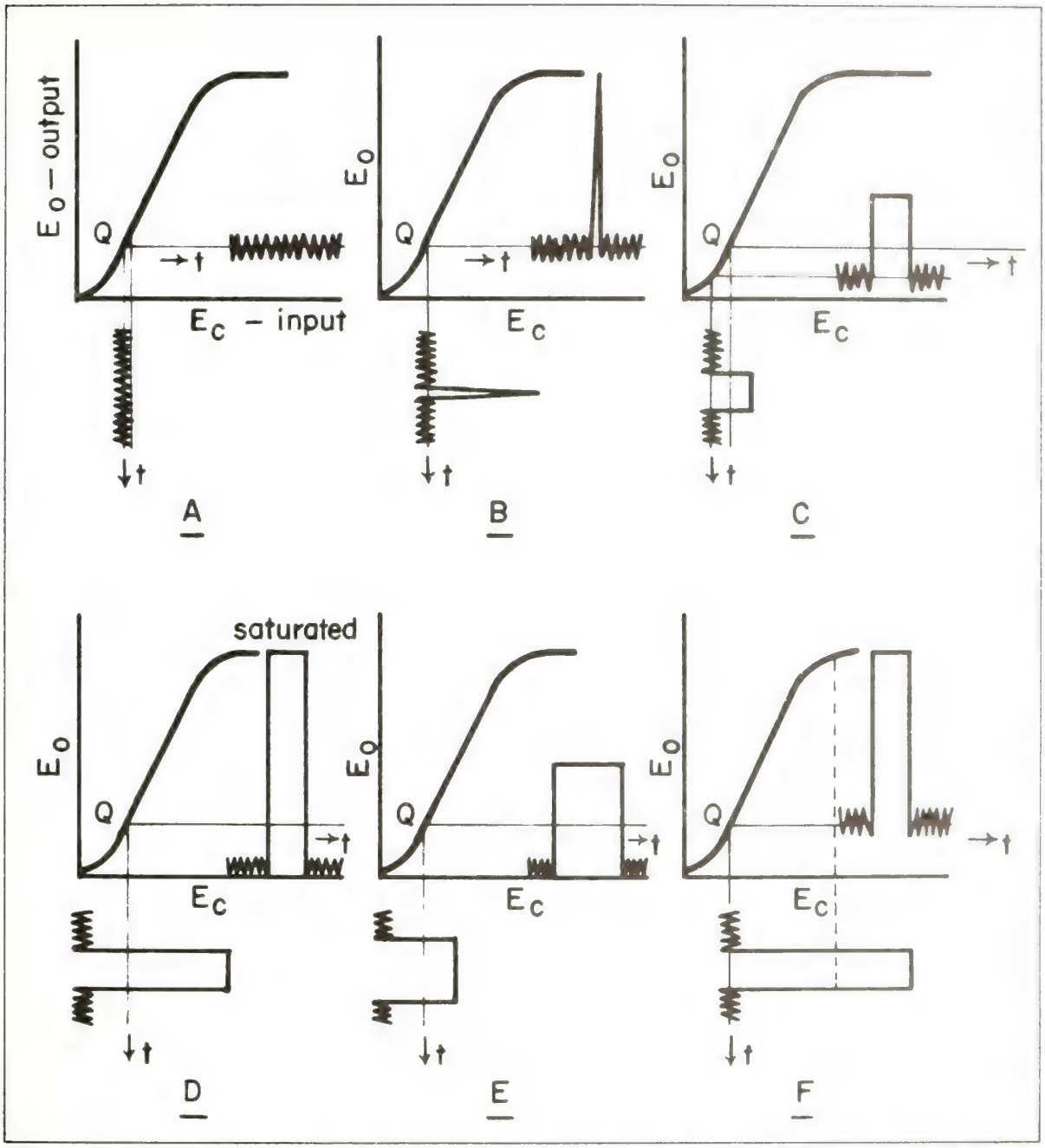

Figure 42.—Effects of a.c. coupling on the transfer curve of a typical amplifier: A, Terrain signal; B, strong, narrow target; C, weak, wide target; D, strong, wide target; E, weak, very wide target; and F, target with d.c. restoration.

in most scanning systems there is a "dead" time when the detector and optics are looking at the inside of the scanner. The scanner temperature is relatively stable and forms a reasonable reference. To insure restoration during the dead time, the switch must be synchronously timed to the optics rotation. A synchronous gate signal closes the switch during part of the dead time, discharging the capacitor to ground and forcing each scan (horizontal sweep) to start from the same reference. The portion of the dead time selec-

ted must be void of any external or varying signals; otherwise, the clamp reference will be destroyed.

Adequate low-frequency response is required; otherwise, overshoot will become a problem. Figure 43 shows the effect of insufficient low-frequency response as the tilt on the top of the wave. The area A_1, enclosed between the input signal and the tilted wave shape, must equal the area A_2. A_2 is overshoot and will return 63 percent of the distance toward zero in one time constant.

$$\tau = \tfrac{1}{2}\ \pi f_1$$

where τ = one time constant
f_1 = low frequency bandwidth.

The area A_2 is more noticeable on imagery than A_1. It appears as a dark area adjacent to hot fire targets and slowly recovers to the brightness of the original terrain features. If the fire area is large, the area A_2 will be large and may obliterate all of the terrain features on the trailing edge of the fire. Figure 16 shows the results of insufficient low-frequency response.

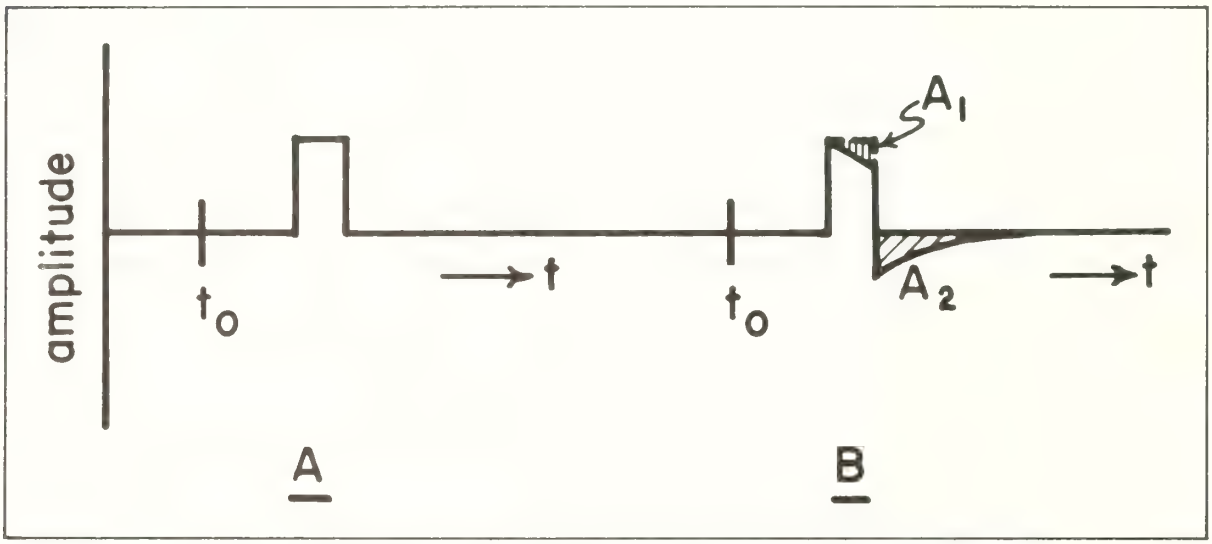

Figure 43.—Effect of insufficient low-frequency response: A, Input; B, output.

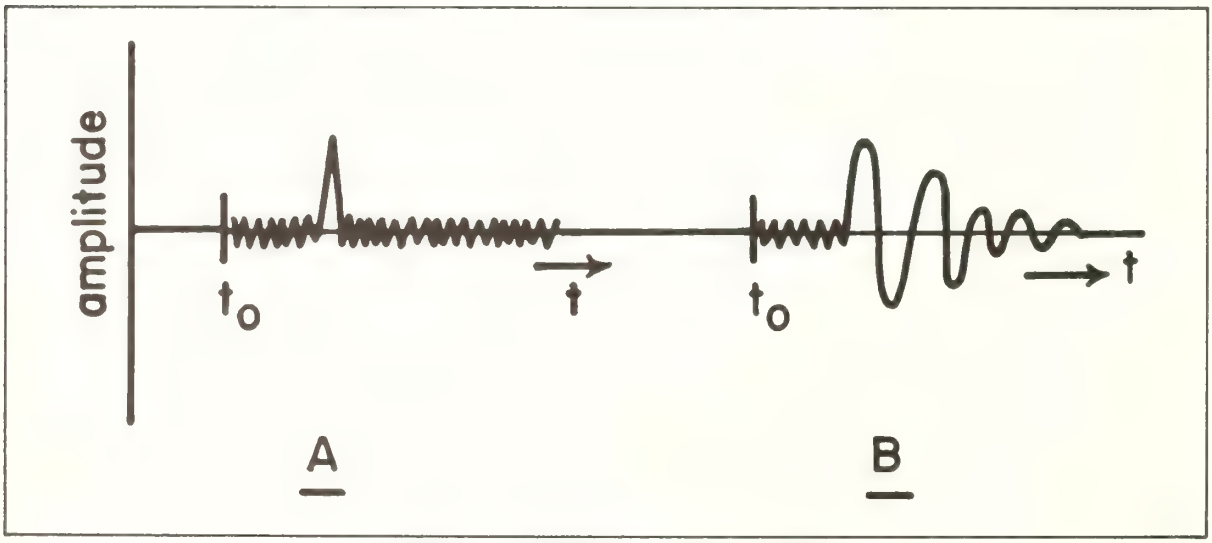

Figure 44.—Ringing: A, Input; B, output.

The system must be able to recover quickly after scanning hot targets. An underdamped system causing ringing (fig. 44) will appear on the imagery as alternate black and white areas following the target as each maxima and minima occurs. Any high-amplitude target or pulse can cause ringing. Ringing is often used to identify small hot targets by multiple spots following the real target, but it destroys detail of adjacent terrain. It should not be used for fire-mapping systems where terrain information is important. Ringing can be eliminated by adequately damping oscillatory components.

When the system is severely overdamped, recovery is slow. The target is elongated (fig. 45), the area adjacent to the fire appears the same color as the fire, and the fire edge is not discernible.

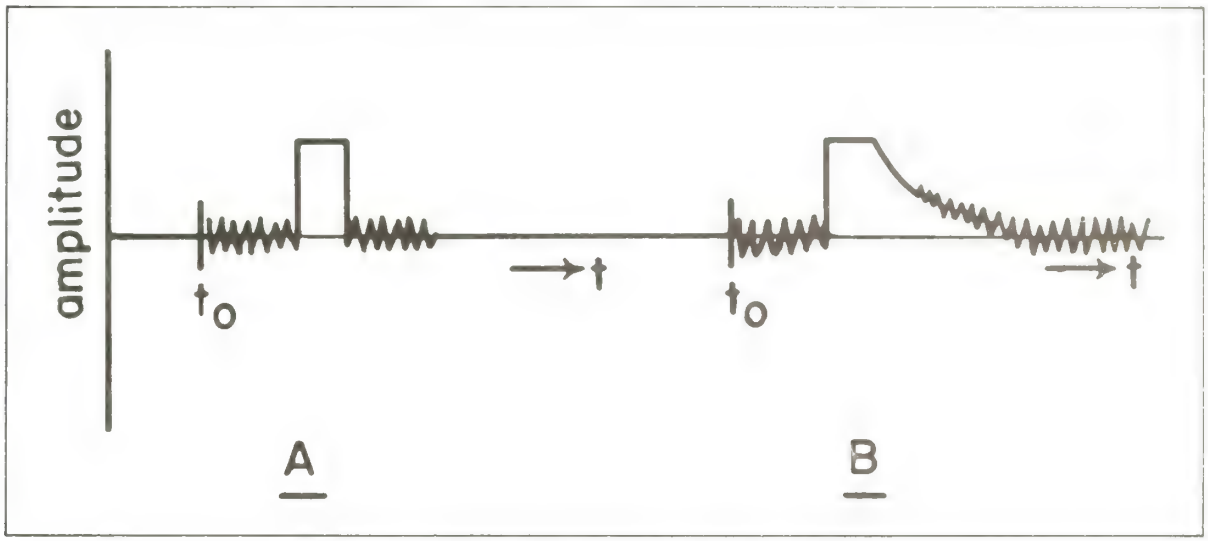

Figure 45.—Target elongation: A, Input; B, output.

APPENDIX V

SUMMARY TABLES:
FIRE OCCURRENCE,
FIRE-MAPPING OPERATIONS

Table 4.–Summary of fire occurrence by Forest Service Regions,[1] 1944-63

Year	Regions									Total fires
	1	2	3	4	5	6	7	8	9	
1944	20	8	10	49	78	26	3	35	9	238
1945	32	3	13	22	71	36	0	31	9	217
1946	13	3	29	27	43	16	1	22	16	170
1947	8	7	16	50	70	11	2	27	4	195
1948	1	9	19	35	38	3	1	18	9	133
1949	14	9	7	28	71	30	0	15	7	181
1950	6	12	38	14	81	12	1	20	2	186
1951	5	8	20	17	78	29	0	20	3	180
1952	5	10	3	11	33	21	25	31	13	152
1953	20	5	25	18	53	3	12	18	6	160
1954	2	7	17	13	45	3	2	20	5	114
1955	3	10	16	8	47	7	0	14	1	106
1956	5	11	53	24	28	2	0	9	5	137
1957	5	0	7	16	35	4	0	4	1	72
1958	13	11	4	27	21	19	0	5	2	102
1959	10	4	15	31	59	22	0	7	2	150
1960	22	22	21	45	51	54	0	13	1	229
1961	29	3	22	37	42	33	0	2	2	170
1962	3	12	12	20	31	13	0	5	6	102
1963	6	17	15	17	25	13	5	26	3	127

[1] *For fires 100 acres and larger, Regions 1-6; for fires 300 acres and larger, Regions 7-9.*

Table 5.—Summary of IR fire-mapping operations, 1964

Name of fire	State	Dates of fire	IR unit on fire	Fire Characteristic on arrival	Fuel type	Fire size		Number sorties					Initial getaway time	Average sortie time over target	Average drop retrieval time	Average IR interpretation time	Day sortie visibility	Use of scan angle		Distance to fire from nearest airport	Average distance, aircraft to ground	Imagery drops		Map drops	All mapping by IR unit		Navigation problems	IR mosaic required
						When called	Final	Per day	Per mission	Runs per	Day	Night						60°	120°			Day	Night	Day	Day	Night		
			Days			Acres		Average					Minutes	Minutes	Minutes	Minutes		Percent		Miles	Miles							
Parsnip	Montana	7/13-14	2	Running	Lodgepole blowdown	120	150	2	3	11	2	1	45	105	15	30	Clear	60.6	39.4	60	2	2	0	0	No	Yes	No	No
Candle Mtn.[1]	Montana	7/23-24	2	Creeping	Lodgepole	10	11	2	3	12	2	1	20	50	DNA[2]	40	Clear	76.3	23.6	15	DNA	0	0	0	No	Yes	No	No
Crazy Creek[1]	Montana	7/27	1	Running	Subalpine	5	15	3	3	7	3	0	55	30	05	10	Clear	79.6	20.4	19	2	1	1	0	No	Yes	No	No
Willow Tree	Washington	8/9	1	Creeping	Sagebrush	1,500	2,370	2	2	10	2	0	75	60	05	60	Clear	0	100.0	35	2	1	0	0	No	No	No	No
Crab Tree	California	8/10-12	2	Spotting	Brush & timber	1,500	2,360	2.5	5	8.8	2	3	105	48	05	100	Clear	36.4	63.6	20	3	6	5	0	No	Yes	No	No
Switchback	Oregon	8/13	1	Creeping	Grass & sagebrush	50	50	1	1	9	1	0	30	30	DNA	40	Clear	80	20	15	DNA	0	0	0	No	No	No	No
Big Creek	Nevada	8/16	1	Creeping	Sagebrush & grass	5,500	6,000	2	2	4.5	2	0	105	40	05	30	Smoke	0	100.0	8	2	1	0	0	No	No	No	Yes
Keas Canyon	Nevada	8/17-19	3	Running	Grass & sagebrush	300	10,350	1.7	9.8	9.2	4	1	20	53	05	40	Smoke	6.2	93.8	70	DNA	0	0	3	Yes	No	No	Yes
Boulder-Magee	Nevada	8/19	1/3	Creeping	Grass	215,000	215,000	1	1	7	1	0	15	40	DNA	20	Clear	28.6	71.4	45	DNA	0	0	0	No	No	No	Yes
Summit	California	8/26-28	2	Running	Oak & brush	2,000	20,000	2	2	11.5	2	2	20	67	DNA	80	Smoke	30.5	69.5	50	1	0	0	0	No	No	No	Yes
French Gulch	California	9/17	1/3	Running	Brush	2	10	1	1	5	1	0	40	20	DNA	20	Clear	100.0	0	10	DNA	0	0	0	Yes	No	No	No
Price[1]	California	9/18	1	Running	Grass & brush	20	300	3	3	14.3	1	2	10	95	DNA	30	Smoke	18.6	81.4	15	DNA	0	0	0	Yes	Yes	No	No
Nuns Canyon	California	9/19	1	Running	Oak & brush	500	3,000	3	3	8	2	1	60	60	05	25	Smoke	0	100.0	10	1	1	1	0	Yes	Yes	No	Yes
Mill Creek	California	9/23	1	Creeping	Oak & brush	250	300	2	2	14	2	0	10	75	DNA	30	Smoke	25	75	30	DNA	0	0	0	No	No	No	No
Coyote	California	9/24-28	4	Running & Spotting	Chaparral	26,000	67,000	2.5	10	9.9	5	5	20	68	DNA	50	Smoke & fog	0	100.0	15	15	0	0	0	No	Yes	Yes	Yes
Eastwood	California	10/20	1/3	Running	Grass & timber	700	800	1	1	4	1	0	80	25	DNA	20	Smog	0	100.0	90	DNA	0	0	0	No	No	No	No
Total			23			253,460	327,716	31.7	51.8	145.2	33	16	710	866		625				507		12	7	3				
Average			1.44	Running—50%		15,841	20,482	2.0	3.2	9.1	2.1	1	44.4	54.2		39.1	Clear—50%	33.9	66.1	31.7		.8	.4	.2	25%	45%	No—94%	No—63%
				Creeping—37.5%													Smoke—38%										Yes—06%	Yes—37%
				Other—12.5%													Smoke & fog—6%											
																	Smog—6%											

[1] Headquarters were not located on roads.

[2] Does not apply

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Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author)

U.S. Department of Agriculture, Forest Serv.
Intermountain Forest & Range Exp. Station
Northern Forest Fire Laboratory

2a [illegible]: Unclassified

2b GROUP:

3 REPORT TITLE

THE USE AND SYSTEM REQUIREMENTS OF INFRARED SCANNERS IN MAPPING WILDFIRES

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

PROJECT FIRE SCAN FIRE MAPPING FINAL REPORT, April 1962 to Dec. 1966

5 AUTHOR(S) (First name, middle initial, last name)

Stanley N. Hirsch, Robert L. Bjornsen, Forrest H. Madden,
Ralph A. Wilson

6 REPORT DATE	7a TOTAL NO. OF PAGES	7b NO. OF REFS
1968	60	22

8a CONTRACT OR GRANT NO.	9a ORIGINATOR'S REPORT NUMBER(S)
OCD-OS-62-174 and OCD-PS-66-17	U.S. Forest Service
b PROJECT NO. Work Unit 2521A	Research Paper INT-49
c	9b OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d	

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13 ABSTRACT

An airborne infrared line scanner sensitive to the 3- to 5-micron spectral region mapped 38 forest fires during the 1963, 1964, and 1966 fire seasons. The imagery obtained provided information about the fire perimeter, relative intensity of burning areas, and spot fire location under conditions when smoke or darkness prevented visual reconnaissance. This report describes the operational methods and equipment used, and gives many examples of imagery collected. It discusses the radiometric and electronic characteristics peculiar to fire-mapping applications. A unique dual Polariod recording camera was developed to provide quickly available imagery for airdrop to fire headquarters.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
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Remote sensing						
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Infrared imagery						

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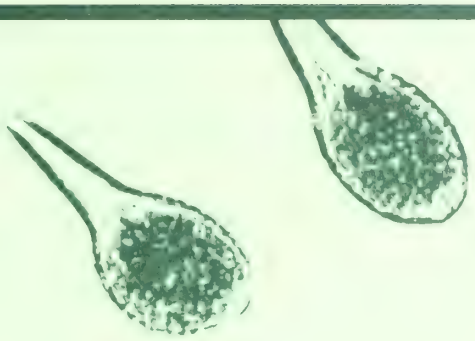
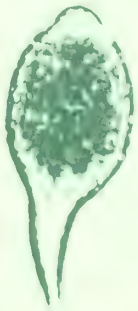
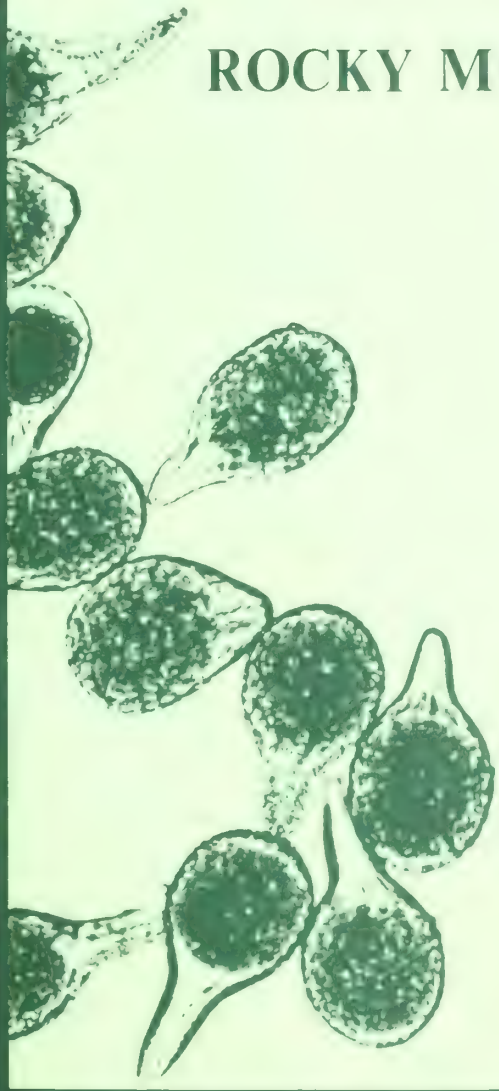


CRONARTIUM COMANDRAE IN THE ROCKY MOUNTAIN STATES

by
R. G. KREBILL





RESEARCH PAPER
INT-50, 1968
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OGDEN, UTAH

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U. S. Forest Service Research Paper INT-50 1968

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INTRODUCTION

Cronartium comandrae Pk. is a heteroecious fungus that lives as an obligate parasite in hard pines and comandras. Although distributed across North America, *C. comandrae* is probably most common now in the Rocky Mountain States. There it produces uredinia and telia on *Comandra umbellata* (L.) Nutt. ssp. *pallida* (A. DC.) Piehl (fig. 1) and aecia on lodgepole pine (*Pinus contorta* Dougl.) and ponderosa pine (*Pinus ponderosa* Laws.). On pine it produces the destructive canker disease (fig. 2) known as comandra blister rust (Hedgcock and Long 1915 and Mielke 1961). This rust was believed to be an important problem in the West only on ponderosa pine until Mielke (1957) reported that it was also causing widespread damage to lodgepole pine in the Rocky Mountains. Concern developed that the rust was intensifying and could become a serious obstacle to the orderly management of lodgepole pine. Subsequent studies of the chronology of comandra blister rust outbreaks in the Rocky Mountain States, made by dating cankers by ring analysis, indicated that infection of lodgepole pine was abundant for several decades prior to about 1945, and since then extremely scarce (Peterson 1962 and Krebill 1965). Thus the comandra blister rust damage that is now apparent in lodgepole pine in the Rocky Mountain States arises from old outbreaks of infection and will not increase unless future outbreaks occur. To better evaluate the potential threat of this rust, we must have a thorough understanding of the causes of outbreaks.

It has long been suspected that fluctuations in the abundance of comandra might influence the occurrence of comandra rust outbreaks in pine. Meinecke (1928) indicated that such changes were major factors regulating outbreaks in ponderosa pine. Some evidence was provided by a severe outbreak of comandra rust in the Shasta River drainage of northern California. When the site was examined in 1914 by J. S. Boyce, heavily infected comandra occurred commonly among recently infected ponderosa pine (Wagener 1960).[1] In the same area nearly 50 years later Wagener (1960)[1] found that the rust was still common, but both comandra and young cankers in pine were scarce.

In the Rocky Mountain States fluctuations in comandra populations are poorly documented. Mielke (1957) suggested that changes in comandra abundance might be occurring in the Intermountain area, and Laycock and Krebill (1967) present some evidence of change in long-term study plots. Also, the fact that it is now difficult to find comandra near some areas where old pine infections are abundant (Peterson 1962 and Krebill 1965) indicates reduction of comandra, unless the infections were due originally to long-distance spread of the rust.

The causes of changes in abundance of comandra are even less well known than the influence of such changes. Wagener (1960)[1] suggested that closing of an overstory might have reduced comandra in the Shasta River drainage outbreak area. This idea has merit since comandra does not survive in deep shade. Meinecke (1928) suggested that continual infection of comandra over a number of years following a buildup of comandra rust in pine causes comandra populations to decline and remain at low levels until the rust dies down in pine; then comandra can reestablish itself and set up conditions for new waves of pine infection. This sequence of events might occur on sites where comandra is not a stable member of a community. However, comandra is commonly abundant now near most old outbreak areas in the Rocky Mountain States, despite frequent heavy infection of the plants. The suggestion has also been made that comandra has increased in the West because of overgrazing (Kimmey 1958 and Mielke 1957 and 1961), but a more recent evaluation casts doubts on this idea (Laycock and Krebill 1967).

Although presence of the alternate host is a requirement for spread of the rust, climatic conditions suitable for infection and development also play a large part (Wagener 1960,[1] Mielke 1961, Krebill 1965, and Powell 1965). The present study improves our understanding of this phase of the epidemiology of comandra blister rust in lodgepole pine by revealing the influence of some physical factors of the environment on the life cycle of *C. comandrae* and by relating these findings to the phenology of the hosts and parasite in a portion of the Rocky Mountains.

[1] Wagener, W. W. *Sporadic changes in comandra rust in California and Nevada*. [illegible] Western Int. Forest Dis. Work Conf., Sun Valley, Idaho. Unpublished [illegible]

Figure 1.– *Comandra umbellata* ssp. *pallida*, host plant for the uredinial and telial stages of *Cronartium comandrae* in the Rocky Mountain States.

Figure 2.– *Cronartium comandrae* canker in lodgepole pine in Custer National Forest, Montana. Bark was removed by rodent chewing, as is typical in the West.

SPORE VIABILITY AND GERMINATION

To explore the influence of environmental conditions on spores during dissemination and germination, many experiments were run under controlled and monitored environmental conditions. Experiments were made to investigate all spore stages involved in infection of comandra and pine, that is (1) aeciospores on pine, with ability to infect comandra; (2) urediniospores on comandra, with ability to reinfect comandra plants; (3) teliospores in telia on comandra, which form basidiospores; and (4) basidiospores which may infect pines.

AECIOSPORES

Annual crops of aeciospores are produced in aecia from perennial mycelium in live bark of cankers of pines. At maturity, aecial peridia rupture and expose dark-orange masses of many thousands of teardrop-shaped aeciospores. These spores are disseminated by wind and function as the primary inoculum for infection of comandra.

Effects of Temperature on Germination

Method.–Aeciospores collected in June from recently ruptured aecia were tested for their ability to germinate at several temperatures. Six samples representing Cache, Targhee, Teton, and Wasatch National Forests were tested. Spores were collected with a small cyclone separator, stored in gelatin capsules, and kept cool until tested within a few days. Collodion membranes floating on distilled water in petri plates were used as the substrate for germination. These membranes were made by pressing large drops of collodion between two glass slides, separating the slides, air-drying the exposed surfaces, and finally floating the membranes off onto water. Such membranes were uniformly a few microns thick and proved excellent for aeciospore germination. Small masses of spores were blown through a cyclone separator into a 40-cm.-high settling tower where spores fell onto the test membranes. Germination was simultaneously tested at 5° C. intervals from 3° to 33° C.±0.5° C. After spores had been incubated 24 hours in darkness, a sodium hypochlorite solution (1 percent available Cl) was atomized onto test surfaces to inhibit further germination. Percent germination was determined by counting at least 200 spores, and length was measured in 20 germ tubes. Counts and lengths were taken using a microscope; fields of view were not chosen systematically, but instead the observer attempted to scatter views over the test surface by moving the slide more or less at random. Evaluations of germination of other spore stages presented in this paper were made by this technique unless otherwise indicated.

Results.–Although germinating aeciospores frequently formed several germ tubes, one tube usually became dominant (fig. 3). When both percent germination and length of dominant germ tubes are considered, temperatures between about 8° and 18° C. are most favorable for vigorous germination, but good germination occurs over a broader range (fig. 4). Only at the extremes of 3° and 28° to 33° C. was germination poor.

Figure 3.–Germination of *C. comandrae* aeciospore after 24 hours incubation (X 200). Note the distinctive teardrop shape of nearby aeciospores.

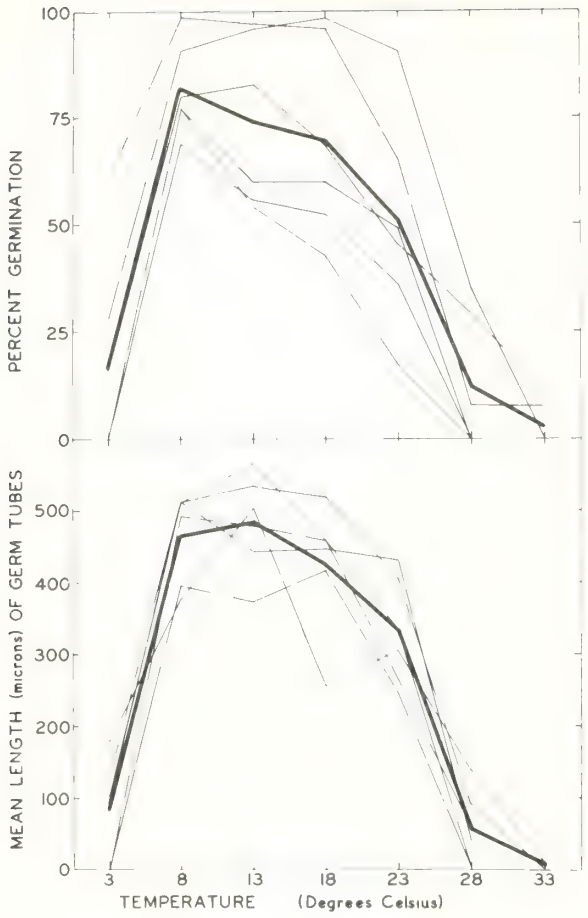

Figure 4.–Germination of aeciospores after 24 hours' incubation at several temperatures. The darker lines are means of the individual samples.

An exploratory test also was conducted to determine how quickly aeciospores germinate and germ tubes grow. Methods used to collect and prepare spores were similar to those described above, but only one collection (Cache National Forest) was tested. Germination of spore groups was stopped after incubation periods varying from 3 to 48 hours. Results indicate that most viable spores germinate within the first 3 hours of incubation at favorable temperatures and that germ tubes continue to grow for more than 24 hours (table 1).

Effects of Light on Germination

The tests of temperature effects were run in darkened chambers and probably indicate what would happen at night in field conditions. In other tests, aeciospores germinated equally well in low light such as might be present on cloudy days. Germination was nil in tests in direct sunlight, but in the field there would rarely be sufficient moisture for germination while there was bright sunshine. Apparently contact with free water is necessary, as evidenced by failure of spores to germinate when tested on glass surfaces in moist chambers if free water has not contacted spores.

Effect of Exposure on Viability and Infectivity

Tests also were run to determine how well the disseminated spores could withstand the kind of waiting period that may pass in the field before moisture and temperatures become favorable for germination. Fresh aeciospores were deposited on shoots of live comandra plants in a glasshouse where temperatures between 10° and 21° C. were maintained. Surface temperatures[2] of comandra leaves remained within a few degrees of air temperatures. At intervals, leaves were plucked from shoots, pressed lightly against 2 percent water agar, and removed. Aeciospores were thereby transferred to the stickier agar surface. Examination showed that aeciospores had not germinated during their exposure on leaves.

Aeciospores on water agar were then placed in moist chambers, and incubated at 18° C. for 24 hours. Examination proved that some aeciospores had remained viable more than 20 days (table 2) at these rather mild conditions.

Infectivity of aeciospores was tested after the spores were exposed to field conditions in Cache National Forest at about 6,000 feet elevation. During 1966, aeciospores were deposited on comandra shoots at various times in an area where natural infection occurs only in unusual years. (None was detected during these tests.) The ability of aeciospores to remain infective was estimated from the degree of development of uredinia on test plants after a period of mild, moist weather that would allow infection. A hygrothermograph in a shelter described by Hungerford (1957) and a recording rain gage within 50 feet of all test shoots provided data on time elapsed between deposition and conditions possible for germination. Uredinia developed on a few leaves of one plant; aeciospores had been deposited 3 days before a trace of rain that made conditions favorable for germination. Other plants on which spores had been deposited 6, 10, and 22 days before conditions

[2] *Measured with thermocouples of overlapped and soldered wires 0.05 mm. in diameter.*

Table 1.–*Influence of time on germination of aeciospores at cool, moderate, and warm temperatures*

Time (hours)	Germination			Mean germ tube length		
	Temperature (degrees C.)			Temperature (degrees C.)		
	8	18	28	8	18	28
	Percent			*Microns*		
3	85	66	0.0	50	140	0
6	78	66	0.0	126	278	0
12	87	70	0.5	363	421	40
24	94	72	1.0	451	495	95
48	91	75	1.0	598	526	70

became favorable for germination displayed no signs of the rust. Comparison of measurements made with thermocouples under similar conditions in Cache National Forest suggests that leaf surfaces had commonly reached 25° to 35° C. at midday. This ability of aeciospores to retain viability for even a few days under severe summer field conditions certainly must enhance spread of *C. comandrae* to comandra.

UREDINIOSPORES

Following infection, annual mycelium develops in leaves and stems of comandra. This soon gives rise to uredinia, which rupture and expose hundreds of yellowish ellipsoidal urediniospores. These spores are disseminated by wind and function as secondary inoculum for additional infection of comandra. This spore stage can quickly intensify the rust in comandra over distances of several miles.

Fresh urediniospores collected in July were tested for their ability to germinate at various temperatures. Tests were run with spore samples from Cache and Wasatch National Forests, and from greenhouse plants that had been inoculated with Cache National Forest spores. The techniques of collecting spores, depositing them on test substrate, and analyzing results were similar to those used in testing aeciospores. However, 2 percent water agar (about pH 6.7) was used exclusively as the test substrate for urediniospores.

Germination of urediniospores was commonly by multiple germ tubes, one of which usually became dominant (fig. 5), but single germ tubes were frequent. Most viable urediniospores produced recognizable germ tubes within the first 3 hours at favorable conditions, and germ tubes grew for more than

Table 2.–*Viability of aeciospores after exposure on comandra shoots in a glasshouse*

Exposure time (days)	Germination[1]	Mean germ tube length[2]
	Percent	*Microns*
0	34	299
5	46	300
11	20	242
21	16	209
28	0	0

[1] *Based on 200 spores*
[2] *Based on 10 germ tubes*

24 hours (table 3). On the basis of both percent germination and length of germ tubes at 24 hours, germination seemed best between 13° and 23° C. and poor at 3° C. and at 28° C. or higher (fig. 6). Like aeciospores, urediniospores germinated equally well in low light (such as might occur on cloudy days) and in darkness, but did not germinate in bright sunlight.

Urediniospores were also deposited on comandra shoots in the Cache National Forest plot mentioned earlier. In two trials in which 10 days of conditions unfavorable for infection followed deposition, no shoots became infected. However, uredinia developed on shoots in two trials in which only 6 days of unfavorable conditions followed spore deposition. Thus, even during short dry spells in a warm summer, dissemination of urediniospores can lead to infection of comandra.

TELIOSPORES

Telia contain up to several hundred teliospores bound firmly together as hairlike projections on comandra leaves (fig. 7) and stems. As soon as conditions are favorable, each teliospore may germinate in place and form a basidium and (usually) four basidiospores that are disseminated by air (Hedgcock and Long 1915). This process, referred to here as basidiospore casting, may lead to the dispersal of many hundred airborne basidiospores from each telium. Thus telia and teliospores are not themselves disseminated, but produce the wind-disseminated spores that infect pines.

Effects of Humidity on Germination

To determine whether saturated air is necessary for germination of teliospores, telia were tested in petri-plate chambers in which humidity was controlled by saturated salt solutions or distilled water (table 4). Excised telia from comandra leaves were stuck by their basal ends to petrolatum on the inside of petri-plate covers, and glass slides were placed beneath the telia to catch dispersed basidiospores. Plates were sealed and incubated in darkness at 20° ±0.1° C. for 24 hours. Slides were then examined microscopically for the presence of basidiospores. They were found on slides in chambers in which relative humidity was 100 percent, but not on slides in chambers in which humidity was 98 percent or lower (table 4).

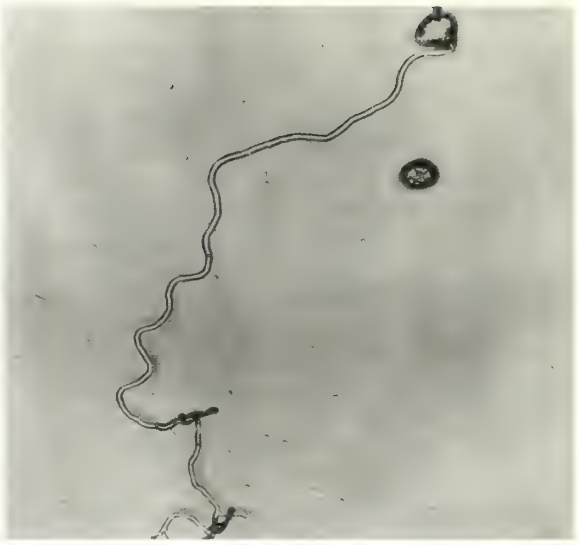

Figure 5.--Germinated urediniospore after 24-hour incubation (X ~~437~~ 175).

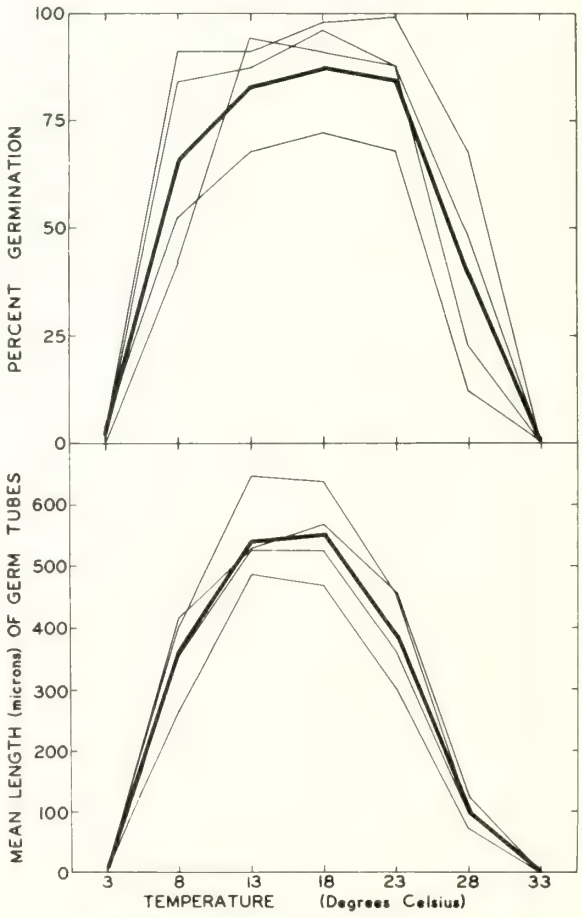

Figure 6.–Germination of urediniospores at several temperatures after 24-hour incubation. The darker lines represent means of four individual trials.

Table 3.--*Influence of time on germination of urediniospores at cool, moderate, and warm temperatures*

Time (hours)	Germination			Mean germ tube length		
	Temperature (degrees C.)			Temperature (degrees C.)		
	8	18	28	8	18	28
	Percent			*Microns*		
3	86	96	67	53	157	64
6	95	94	87	135	270	84
12	93	96	76	311	376	109
24	99	98	83	420	520	116
48	96	99	88	450	541	124

Effects of Temperature on Germination

Method.--Fresh telia from inoculated comandra in a greenhouse were placed in petri-plate moist chambers maintained at various temperatures, to an accuracy of about ±0.5° C. Excised telia were attached vertically by their bases on 2 percent water agar on the insides of plate covers. When teliospores germinated, basidiospores fell onto plates containing 2 percent water agar (adjusted with HC1 to pH approximately 2.0 to prevent germination of the basidiospores, which makes counting difficult). After 3, 6, 12, 24, 48, and 72 hours, the covers were rotated by hand so that time of spore casting could also be determined. Teliospore germination was evaluated by counting the basidiospores cast from whole telia.

Results.–Excellent casts of basidiospores were produced at temperatures of 13° to 23° C.; casts were fair but slower at 8° C., and poor at 6° and 24° C. (fig. 8). No basidiospores were cast at 3° or 25.5° C. and higher. At 25.5° C., basidia formed but no basidiospores developed. At 28° and 30.5° C., not even basidia formed. Comparisons by Duncan's New Multiple Range Test (Duncan 1955) at the 0.01 level indicated that the excellent casts at temperatures 13° to 23° C. were not significantly different from each other at 12 and 24 hours, but were better than casts at other temperatures and continued to be greater throughout the remainder of the 72-hour incubation period. In other similar tests the relative position of the maximum casts varied between 13° and 22° C., but at 25° C. and higher there were never any casts, and longer incubations were always required at temperatures less than 13° C. These results are a refinement over an early report by Mains (1916). He reported no germination at 10° and 30° C., fair germination at 18° C., and good germination at 24° C.

Figure 7.–Telia of *Cumanetia comandrae* on comandra leaves (X 9). Telia are common on both upper and lower surfaces of leaves and on stems of *Comandra umbellata* ssp. *pallida*.

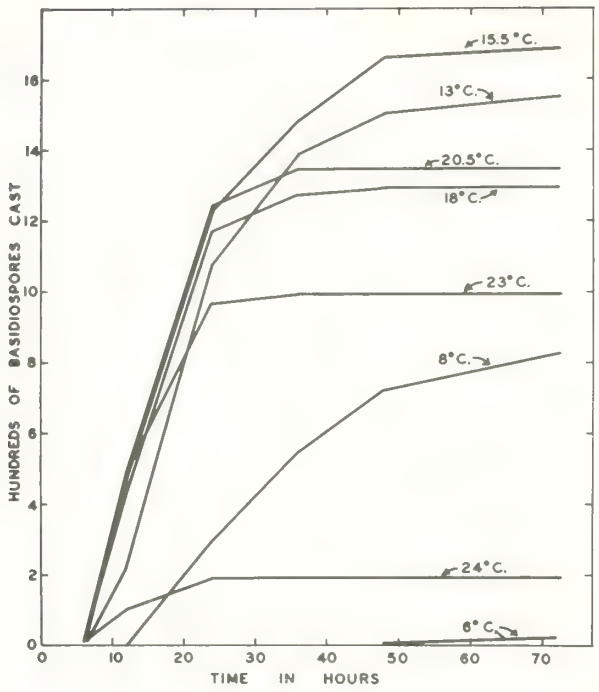

Figure 8.–Germination response of teliospores to several temperatures. Each curve represents the cumulative mean from 10 telia.

Figure 9.–Clock-drive unit that automatically rotates cover of large petri plate. When telia are attached to the cover, basidiospores are cast onto the stationary bottom of the petri plate so as to reveal by their position when casting occurred.

Effects of Freezing and Heating on Viability

The effect of freezing temperatures on viability of teliospores was tested under laboratory conditions. Fresh telia produced from greenhouse inoculations were excised from comandra leaves. These telia were then subjected to below-freezing temperatures such as occur during mild to severe frosts in the field (table 5). Each treatment was replicated with nine telia of equal size for each temperature. After exposure, telia were incubated at 18° C. for 72 hours in moist chambers and basidiospores cast were counted.

As shown in table 5, freezing reduces the ability of telia to cast basidiospores. This effect occurred whether or not the process of germination had already begun at the time of freezing; basidiospore casts were suppressed in telia frozen immediately after removal from comandra leaves and also in telia previously incubated under conditions favorable for germination. Suppression increased with increasing severity of freezing treatment.

Fresh *C. comandrae* telia from Cache National Forest were also subjected to warm temperatures to determine if heat might suppress subsequent casting of basidiospores as it has been shown to do in *C. ribicola* (Van Arsdel et al. 1956). All telia in each trial were of nearly equal size, and no previous germination had occurred. Five telia were used for each treatment. Both dry telia (placed in paper bags) and telia in moist chambers were exposed to heat treatments (table 6). As in earlier tests, telia were then placed in moist chambers at 18° C. for 72 hours and basidiospores cast were counted.

Heat suppressed the ability of teliospores to germinate (table 6) but rather long periods of exposure to warm temperatures were necessary. It would seem unlikely that in pine areas of the Rocky Mountain States warm temperatures would last long enough to alter teliospore germination.

Influence of Light on Germination

To test the influence of light, freshly excised telia from inoculated comandra were stuck to the inside covers of petri plates, as described earlier for temperature studies, and were placed in natural or artificial light or in darkness. The covers were contin-

Table 4.--*Influence of relative humidity on teliospore germination at 20° C. ± 0.1*

Relative humidity (percent)[1]	Saturated salt solution	Mean number basidiospores cast[2]
20	KAc	0
70	KCl + NaCl	0
90	$ZnSO_4$	0
98	$K_2Cr_2O_7$	0
100	Water only	960

[1] *Basis for relative humidity values from Winston and Bates (1960) and Kiker and Ross (1956).*
[2] *Based on 5 telia per treatment at each relative humidity.*

Table 5.--*Effects of freezing on teliospore germination*

Freezing period (hours)	Mean number basidiospores cast[1] Freezing temperature (degrees C.)[2]			
	-1	-4	-8	-12
Not preincubated:				
0 (control)[3]	812	589	594	622
6	778	294**	144**	1**
24	511*	212**	101**	3**
Preincubated:[4]				
6	789	422*	46**	0**
24	167**	331**	73**	0**

[1] *Based on 9 telia per treatment at each temperature.*
[2] *Temperatures ±0.5° C.*
[3] *A control group was set aside to correspond to each series of tests at a particular temperature. Sizes of telia within all treatment groups at a single temperature were similar, whereas sizes varied between temperature series.*
[4] *Placed in moist chamber for 6 hours at 18° C.*
andSignificantly less than control at the 0.05 and the 0.01 levels, respectively, as detected by Duncan's New Multiple Range Test (Duncan 1955). Comparisons were made between treatments within each temperature series.*

uously revolved by a clock-drive mechanism (fig. 9) and germination was analyzed according to the numbers of basidiospores that fell onto 2 percent water agar (pH 2) in the plates. In the counting process, the casts were divided into intervals corresponding to 3 hours of cover revolution. These tests were run in a plant growth chamber with 'cool white' fluorescent lights supplemented by incandescents and in a glasshouse on several overcast days. Germination was tested under varying light conditions. Light inside petri plates was about 1,000 foot-candles in the growth chamber and up to 800 foot-candles in the glasshouse (fig. 10). Care was taken during incubation to balance temperatures within dark and lighted plates. (Temperatures were measured with thermistors inside the plates and the plates were moved to warmer or cooler levels of the growth chamber as needed.) Higher levels of light were not included, as it proved impossible with this technique to keep temperatures within limits necessary for germination when more light was supplied.

From the excellent casts of basidiospores indicated in the graph for both light and dark conditions, it appears likely that telia may [illegible] days if temperature and humidity requirements are met.

BASIDIOSPORES

Basidiospores of rust fungi require a suitable environment during dissemination to maintain viability. Basidiospores of other conifer rusts have been shown to be adversely influenced by high temperatures, low humidity, and sunlight (MacLachlan 1935, Hirt 1935, and Spaulding and Rathbun-Gravatt 1926). The influence of these factors was studied in *C. comandrae* basidiospores.

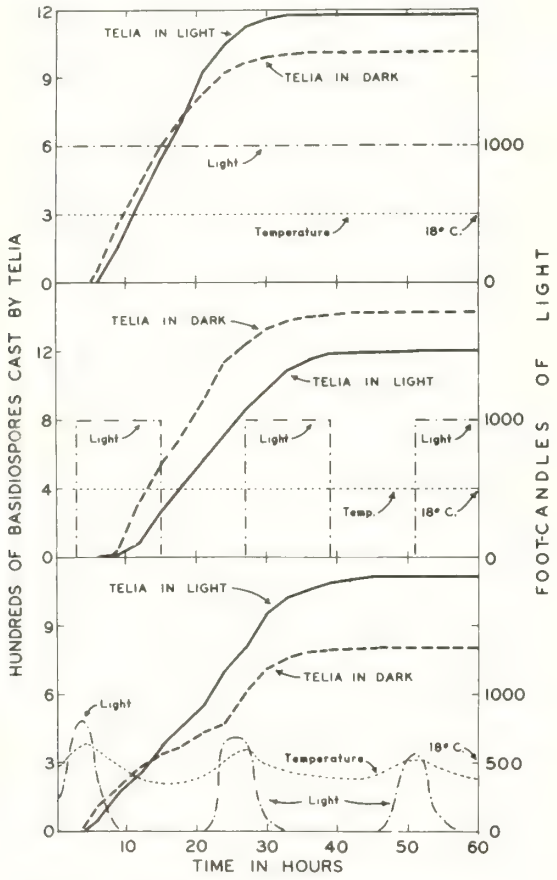

Figure 10.–Germination of teliospores, based on cumulative numbers of basidiospores cast from telia in light and darkness. The upper two graphs represent trials run in the growth chamber. In the first, the "light" group of telia was exposed constantly at the 1,000-foot-candle level. In the second, the "light" group was exposed at regular intervals as shown. The lowest graph represents the trial run in a glasshouse, where the "light" group was exposed to natural intervals of light and darkness. Temperatures were held constant in the growth chamber and fluctuated somewhat in the glasshouse, as shown by the dotted lines.

Freshly formed basidiospores were collected on glass slides and on 2 percent water agar. For collection, glass and agar were exposed for 1 hour beneath germinating telia in moist chambers at 15° to 22° C. The basidiospores were immediately exposed outdoors. During exposure, surface temperatures of the glass and agar were measured with thermocouples. After exposure, the basidiospores were incubated on 2 percent water agar at 18° C. for 24 hours. Viability was then measured by percent germination.

Basidiospores were sensitive to exposure, but survived sunlight well for at least 2 hours when kept in contact with a moist substrate (table 7). Viability declined more quickly in basidiospores exposed directly on glass, even when the slides were shaded by lodgepole pine.

The influence of relative humidity on retention of viability of basidiospores was studied. Basidiospores were obtained by exposing glass slides beneath telia germinating at 18° C. in dark moist chambers. After 1 hour of deposition, the slides were transferred inside a mist chamber to dark chambers in which relative humidity was controlled by glycerol solutions as described by Scharpf (1964). Following exposures of ½, 2, 4, and 20 hours at controlled humidities, basidiospores were transferred inside a mist chamber to 2 percent water agar, and were incubated 24 hours at 18° C. Spore viability was evaluated by percent germination based on at least 200 spores.

Relative humidity had a pronounced effect on survival of basidiospores. Survival diminished with increasing exposure time in less-than-saturated atmosphere (fig. 11) and decreased most rapidly at lower humidities. It was only slightly better at 10° than at 20° C. Thus it would seem that only basidiospores disseminated during damp weather would be viable.

The influence of temperature on germination of freshly cast basidiospores was studied. Spores were incubated in unlighted chambers in which temperatures were controlled to an accuracy of ±0.5° C. After incubation (24 hours except in time tests), further germination was inhibited by application of 1 percent chlorine. Percent germination, based on at least 200 spores, and mean length of 20 germ tubes were then determined.

The percentage of spores that germinated increased for more than 24 hours at 8° and 28° C., but reached its maximum in 6 hours at 18° C. (table

Table 6.--*Effect of high temperatures on subsequent teliospore germination*[1]

Exposure time (hours)	Mean number basidiospores cast[2]				
	Temperatures (degrees C.)[3]				
		26		30	
	Control	Dry	Moist	Dry	Moist
0	850				
4		890	860	567	600
8		674	710	910	655
24		702	372**	396**	149**
48		240**	68**	266**	154**
72		170**	11**	262**	33**

[1] *Based on whole telia prepared as described in text.*
[2] *Based on 5 telia for each treatment.*
[3] *Temperatures ±0.5° C.*
** *Significantly different from control at 0.01 level as detected by Duncan's New Multiple Range Test (Duncan 1955).*

Table 7.--*Effect of exposure to outdoor conditions on viability of basidiospores*

Exposure treatment	Subsequent germination
	Percent[1]
Midday December sunshine in Logan, Utah, at -1° to -6° C. air temperature:	
½ hr. on dry glass	0
½ hr. on water agar	99
2 hr. in distilled water	88
Midday August sunshine (6,000 to 7,000 foot-candles) on Cache NF near Beaver Mountain:	
½ hr. on glass at 24% r.h. and 22° to 29° C.	91
1 hr. on glass at 19% r.h. and 34° to 41° C.	0
½ hr. on water agar at 17° to 22° C.	100
1 hr. on water agar at 17° to 22° C.	100
2 hr. on water agar at 19° to 23° C.	85
Midday August shade (200 foot-candles) near Beaver Mountain:	
1 hr. on glass at 28% r.h. at 25° to 30° C.	29

[1] *Based on a sample size of from 47 to 200 spores.*

8). Germination was usually by a single germ tube that continued growing for more than 24 hours. Excellent germination and germ tube development occurred from about 8°-13° to 23°-28° C., but germination was poor at the extremes of 3° and 33° C. (fig. 12).

In other tests, telia that had been in storage at 5° to 7° C. for several weeks often produced basidiospores, many of which germinated by forming either secondary basidiospores or short (<10μ) broad germ tubes, rather than by forming normal tubes, which generally reach more than 100μ in 24 hours. Such abnormal types of germination are also seen occasionally in basidiospores cast from field collections of older telia, but not in those cast from fresh young telia.

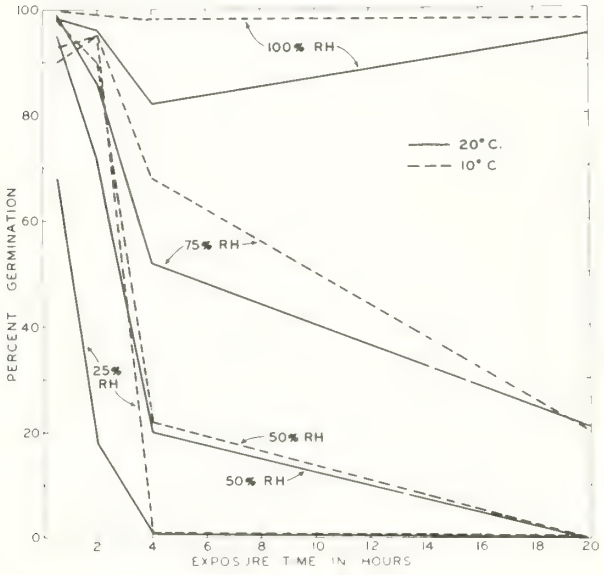

Figure 11.–Survival of basidiospores after exposure to various temperatures and relative humidities, as indicated by subsequent basidiospore germination.

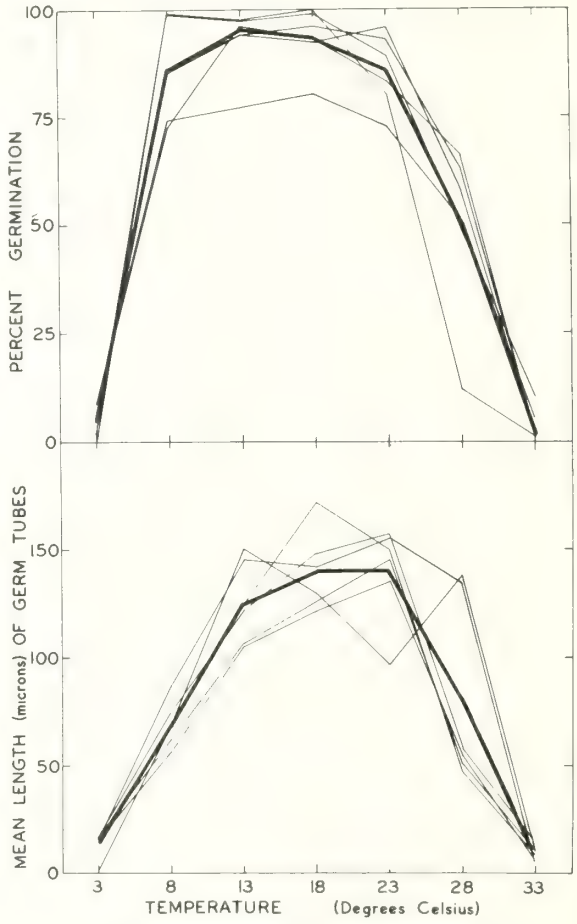

Figure 12.–Germination of basidiospores at several temperatures after 24 hours' incubation. The darker lines are mean curves of the individual trials.

Table 8.–*Influence of incubation time on germination of basidiospores at cool, moderate, and warm temperatures*

Time (hours)	Germination			Mean germ tube length		
	Temperature (degrees C.)			Temperature (degrees C.)		
	8	18	28	8	18	28
	Percent			*Microns*		
3	0	28	6	0	16	8
6	0	100	17	0	26	13
12	64	100	35	18	85	21
24	94	100	54	76	159	29
48	85	100	65	130	243	38

INFECTION

Comandra, jack pine, ponderosa pine, and lodgepole pine have previously been infected with comandra rust in experimental trials (Adams 1919, Anderson 1960, Andrews et al. 1963, and Hedgcock and Long 1915). However, virtually nothing is reported about the processes of infection or the influence of moisture, temperature, or host phenology on infection. Some information on these factors was obtained in the following trials.

COMANDRA

Penetration of comandra was observed with an incident light microscope and with a normal light microscope when leaves were cleared by the lactophenol-chloral hydrate technique (Riker and Riker 1936) and stained with aniline blue. Both aeciospores and urediniospores germinated well on leaf surfaces. Appressoria formed when germ tubes contacted stomates (fig. 13), and infection pegs could be seen penetrating between the guard cells of stomates. This was the only type of penetration seen in comandra.

The influence of temperature during inoculation of comandra was studied under controlled conditions. Comandra that had been growing in flats in Logan for at least a year were used as test plants. At the time of inoculation, shoots were about 2 months old. Inoculum consisted of fresh aeciospores and urediniospores originating in Cache National Forest. Approximately equal numbers of spores were deposited on test shoots by the settling tower method described earlier for aeciospore germination tests. The flats were then placed in controlled temperature (±1° C.) chambers in darkness. Distilled water was atomized intermittently in the chambers and small water droplets remained on leaves throughout the inoculation. After specified times in the mist chambers, the flats were moved to shaded portions of a well-ventilated greenhouse until moisture on the shoots dried (5 to 20 minutes). The flats were then placed on greenhouse benches and shoots were examined periodically for the presence of uredinia. A few days after the emergence of the first uredinia, the numbers of infection spots (evidenced by yellow color, swelling, and uredinia) on test shoots were counted.

Infection of comandra occurred over a wide range of temperatures with both aeciospore and urediniospore inoculum (table 9). Although infection spots increased with longer mist periods, 12 to 24 hours was sufficient for abundant infection at moderate temperatures. In followup trials, infection occurred in as little as 5 hours in a mist chamber at about 20° C.

In other experimental inoculations, it was easy to infect comandra shoots in a juvenile stage (1 week after emergence, when the purple shoots were only a few centimeters tall), through maturity, and until normal leaf abscission. Thus it appears that comandra is highly susceptible at any stage of development during the growing season.

At greenhouse conditions of about 13° to 24° C., 10 to 15 days generally passed from the

Figure 13.—Appressorium and infection peg of a germ tube attached to stomate on a comandra leaf (X 850).

Table 9.–*Influence of temperature and time on infection of comandra in mist-chamber inoculation tests*

Inoculum and time in mist chamber (hours)	Mean number infections per leaf						
	Temperature (degrees C.)						
	3	8	13	18	23	28	33
Aeciospores:							
0 (Control)[1]	0	0	0	0	0	0	0
12	0	5	0.2	6	8	Shoots died[2]	
24	0.1	7	7	9	8		
48	0	8	8	26	8		
72	0	9	9	25	8		
Urediniospores:							
0 (Control)[1]	0	0	0	0	0	0	0
12	1	4	6	9	7	Shoots died[2]	
24	2	8	7	9	10		
48	3	8	11	10	10		
72	5	7	11	11	10		

[1] *A corresponding control group was set aside for each temperature series for each type of spore.*
[2] *Apparently killed by environmental factors associated with the warm mist treatment and subsequent drying.*

beginning of an inoculation until uredinia emerged through leaf surfaces, although the uredinia were sometimes visible beneath the epidermis after only 6 or 7 days. Telia generally emerged 20 to 30 days after inoculation, but in one instance they developed after only 10 days had elapsed. Sometimes, especially late in the growing season, the uredinial stage is bypassed and only telia form. Artificial inoculations we made in Cache National Forest in spring generally resulted in uredinia in 2 to 3 weeks and telia in 4 to 6 weeks.

PINE

All reported experimental infection of pines has been with telial inoculum that had presumably passed through the basidiospore stage before the infection. Meinecke's (1929) attempts to inoculate pines with aeciospores by his wounding and spore-showering techniques, which were successful with *Peridermium harknessii,* were unsuccessful with *C. comandrae,* as might have been anticipated with this heteroecious rust fungus.

The possibility of mycelial transfer by rodents and insects has also been investigated. More than 100 attempts in the field to transfer the rust by bark inserts and bark patch grafts (means used successfully by Hedgcock and Hunt 1920 and Patton 1962 with other conifer stem rusts) have failed for *C. comandrae.* This might indicate that the odds are against successful mycelial transfer by insects or rodents, particularly under natural conditions that would probably be harsher than those in the trials. Therefore it seems reasonable that pine infection in the field results only from infection by basidiospores.

My attempts to detect penetration by means of tissue clearing and incident-light microscopy have failed, so the process of infection remains a mystery. However, successful inoculations of seedlings give clues to the influence of temperature and moisture on infection and to the tissues that are susceptible.

Method.–Lodgepole pines midway through their third growing season were inoculated in a mist chamber within a growth chamber. Temperatures were controlled within the mist chamber ±1° C. and the chamber was dark except in one experiment using a programmed temperature cycle.[3] Inoculum from Cache National Forest consisted of fresh comandra shoots with viable telia, placed over the test pines.

[3] *Seedlings were exposed to a cycle of 12 hours of darkness at 5° C., followed by 12 hours of light (about 1,000 foot-candles) at 15° C. The test began with 3 hours of light.*

After remaining in the inoculation chamber for 1, 2, and 3 days, the pines were placed in a greenhouse until autumn and then moved to outdoor cold frames.

Results.--Seedlings were examined frequently over a period of 2 years. No infections developed on 50 pines reserved as controls. On inoculated seedlings, no positive indication of infection was noted until the summer following inoculation. Then, infections could be identified only by stem swellings and pycnial droplets that exuded in August and September. Aecia formed and cast aeciospores in May of the next year (fig. 14). The most abundant infection resulted from inoculations at temperatures of 15° and 20° C.; 24 hours in the mist chamber was apparently sufficient for the formation and dispersal of basidiospores, and their germination and infection of pine tissues (table 10). Infection also occurred under less favorable conditions but no infection occurred at 5° or 25° C. From the position of the infections, it was determined that 13 had entered through current year shoots, 11 had entered 1-year-old tissue (three of these might have entered through current year adventitious shoots), and none had entered 2-year-old tissue.

Although no outward signs of the rust were evident in needles, microscopic examination of sections showed rust hyphae in needles attached to stem swellings. Unfortunately it could not be determined if the rust had entered the needles first or had grown out into them from infected bark. However, needles would seem a likely place for infection since direct stem infection by basidiospores of conifer rust fungi has been reported only in primary tissue of current year stems. In the pines tested here, stem elongation had terminated at least a month before inoculation, and periderm tissue had formed.

Figure 14.–Lodgepole pine 21 months after experimental infection with telia of *Cronartium comandrae* from Cache National Forest. Ruptured aecia are present on the upper portion of the swollen stem.

Table 10.–*Influence of time and temperature on experimental infection of lodgepole pine*

Time in mist chamber (hours)	Ratio of infected pines to total pines					
	Temperature of mist chamber (degrees C.)					
	5	10	15	20	25	5-15[1]
24	0/8	0/9	3/11	1/8	0/8	1/8
48	0/8	0/10	3/12	5/8	0/8	1/8
72	0/8	1/10	3/12	1/6	0/8	4/12

[1] *Approximation of natural conditions as described in text, footnote 3.*

OVERWINTERING

Like the other Cronartium rusts of pines, *C. comandrae* overwinters as mycelium in live bark of its pine hosts, and aeciospores may be produced from the same canker for many successive years (Arthur 1929 and Hedgcock and Long 1915). Being an obligate parasite, *C. comandrae* dies along with its host, but the two commonly survive together for a few years or even a few decades. In some unusual instances the mycelium of a single canker may remain active for more than a century (Krebill 1965). Aecial production in long-lived infections often is limited and may not occur in many years, especially when mycelium is in bark that is not very active physiologically. In the form of its long-lived mycelium, *C. comandrae* can exist for long periods in pine stands even when there is no new infection.

C. comandrae is unable to overwinter in comandra in mountain areas near susceptible pines. Infections on stems of comandra are common, but microscopic examination indicates that the rust fungus does not grow down the stems into rhizomes. Thus when the shoots die in the fall, the comandra plant is freed from the rust. Indeed, transplants of severely infected comandra collected in fall from Cache and Teton National Forests sprouted free of rust in Logan the following spring. Likewise, experimentally infected comandra have always sprouted free of rust after overwintering outdoors in Logan.

Although there is no field evidence to suggest that *C. comandrae* can overwinter in the mountains, it may possibly overwinter free from pines in the Great Plains of eastern Colorado (Bethel[4]). The mode of such overwintering is unknown and the observations reported could even be misinterpretation of long-distance dissemination of aeciospores or urediniospores.

[4] *Bethel, E. Some early collections of west American fungi. Unpublished manuscript, filed in Intermountain Forest and Range Exp. Sta., Logan, Utah. 1925.*

PHENOLOGY OF LODGEPOLE PINE, COMANDRA, AND *CRONARTIUM COMANDRAE* IN THE ROCKY MOUNTAIN STATES

Development of comandra blister rust and the corresponding development of comandra and lodgepole pine were studied from 1962 to 1966 in the western part of the Rocky Mountain States. Several plots for which general phenology data were recorded are listed below. The plots are named for the National Forests in which they are located.

Teton–Wyoming, near Goosewing Guard Station in the Gros Ventre River drainage south of Kelly at 7,250 feet with a southern aspect.

Targhee–Idaho, near Pine Creek north of Swan Valley at 5,850 feet with a southern aspect.

Bridger–Wyoming, near Fremont Lake east of Pinedale at 8,500 feet with a western aspect.

Sawtooth–Idaho, on Cassia Plateau west of Oakley at 7,400 feet on a slight northwest slope.

Wasatch–Utah, near Beaver Creek east of Kamas at 7,500 feet elevation on a slight southwest slope.

Each plot consisted of lodgepole pines with 10 marked cankers and 10 marked branch shoots on the same trees, and 10 comandra shoots in nearby open areas. Length of marked shoots and occurrence of spore-producing structures were recorded at least once each month of the growing season.

Analysis of these plots (fig. 15) tells us much about the phenology of the hosts and parasite in the Rocky Mountains. Comandra sprouts early in the spring; it emerges through the soil soon after snowmelt in mid-May or late May. Shoot growth is rapid through June and into early July. Foraging by rabbits and ungulates reduces shoot height, and in autumn after severe frosts, leaves dehisce and stems die. Branch shoots of lodgepole pine begin growing in early June and continue elongating through July. Aecia of *C. comandrae* emerge about the same time that lodgepole pine shoots begin growth and the aecia remain abundant through early summer. Some aecia continue dispersing spores well into autumn and, rarely, new aecia form in early autumn. Pycnia exude after the onset of aecia from late June through August, some continuing into September. Uredinia appear in July about the time comandra shoots attain full height growth and the pines are dispersing pollen. By early autumn, uredinia are inactive. Telia usually appear a couple of weeks after the appearance of uredinia and become plentiful in August. They remain abundant until leaves and stems die in autumn.

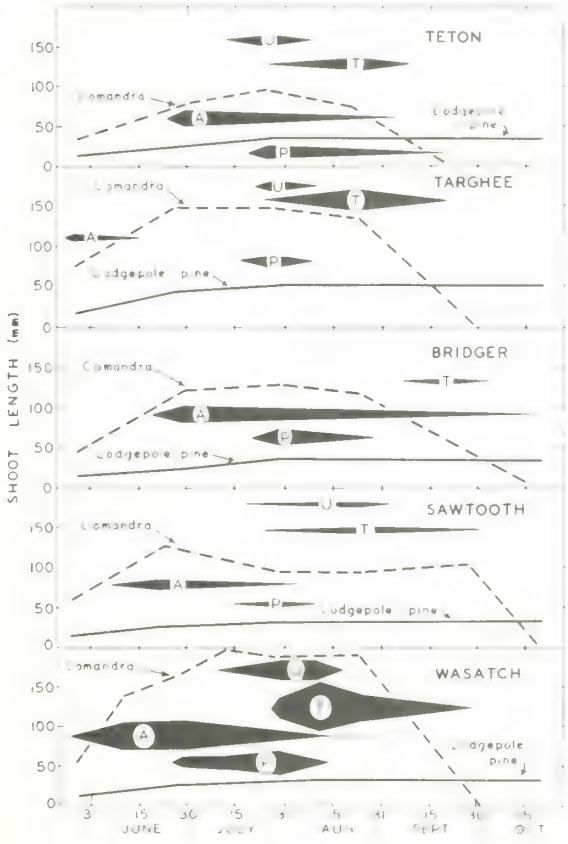

Figure 15.--Phenology of *C. comandrae* and its hosts in several National Forests in 1965. The solid bars represent sporulation in the various stages: A, aecial; U, uredinial; P, pycnial; and T, telial. The vertical extent of the bar indicates frequency of sporulation in relative terms; the horizontal extent of the bar indicates duration on the time scale. The dashed line shows seasonal growth of comandra with reference to the scale of shoot length at left. Growth of lodgepole pine is similarly shown by the solid line.

Elevation

To test the influence of elevation on rust development, four additional plots were established in the Uinta Mountains near the Upper Provo River. All had southwest aspects and were located at elevational increments of approximately 1,000 feet in the lodgepole pine zone of from about 7,000 feet to over 10,000 feet elevation. Comandra was not found above about 8,500 feet in this vicinity even though the rust occurred in cankers near the upper limit of lodgepole pine.

From the evidence of the plots, elevation has a strong influence on phenology (fig. 16). Development of rust was earliest and the season of development was longest at the lowest elevation; with increasing elevation, development of rust was delayed and the season shortened. Since elevation was not so clearly implicated as a factor in results from the other plots (fig. 15), such conditions as aspect and local weather also must affect phenology.

Local Weather

In order to find out more about annual variation in phenology and the influence of local weather, we established plots in the Bear River Mountains of Cache National Forest. Beaver Mountain plot was located at 7,200 feet elevation on a southern aspect in northern Utah, and Fish Haven plot was established at 6,800 feet elevation on a southeastern

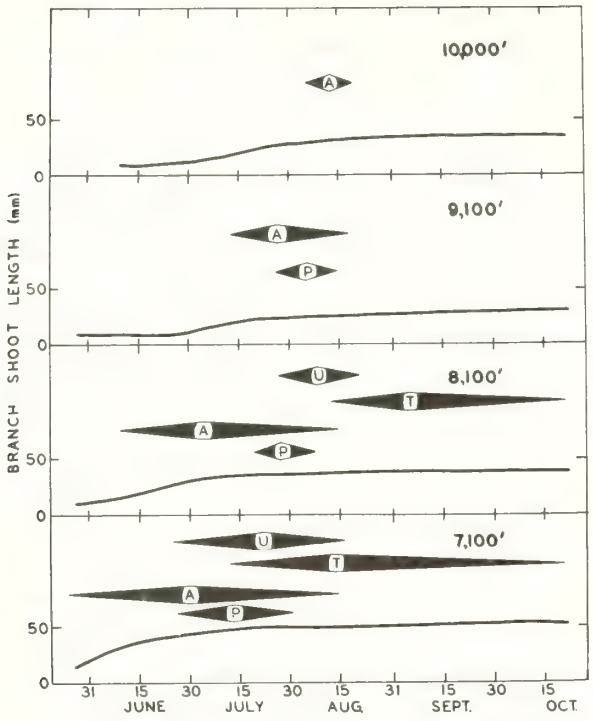

Figure 16.--Phenology of *C. comandrae* and lodgepole pine at four elevations of similar aspect in Wasatch National Forest in 1965. The bars represent presence of spores of various stages: aecial, pycnial, uredinial, and telial. Relative frequency and duration of sporulation are indicated by vertical and horizontal extent of the bar, as in figure 15. Growth of pine in terms of branch shoot length is shown by the curves; comandra was absent at the two higher elevations.

aspect in adjacent Idaho. Temperature and relative humidity were recorded by hygrothermographs in shelters (Hungerford 1957) that were placed so that the sensors were about 4 to 6 feet high near cankers of lodgepole pines and about 0.5 foot to 1 foot high near comandra plants. Precipitation was measured by recording rain gages located in open areas near comandra. Fifteen branch leaders and 30 current-year needles of lodgepole pine, and 15 shoots of comandra were marked and measured weekly. Pollen casting by pine and flowering of comandra were noted. Presence of aecia and pycnial oozing were recorded for 15 cankers in each plot. Development of uredinia and telia on the 15 marked comandra shoots in each plot was also noted. Periods of spore dissemination were determined by spore traps (fig. 17) placed near sporulating structures of infected plants. Seasonal traps consisted of petrolatum- or glycerine-jelly-coated glass microscope slides on a continuously moving belt; an opening above the slides allowed each point on the slides an exposure of 6 hours to deposition of spores by gravity. Trapping was also done intermittently by a suction trap somewhat similar in operation to the Hirst trap (Hirst 1952). Microscopic examination of slides showed the presence of spores, and their position along the slides showed when spores were trapped.

A summary of spore-trapping data, host phenology, and weather is presented in figures 18, 19, and 20. Although aecia were present on some cankers from early June to late September, the vast majority of aeciospores were dispersed in June and July. During June, general rain associated with frontal storms is fairly common in this area. Comandra has already made most of its shoot growth by the time aeciospore inoculum arrives. Perhaps this rust-free period accounts for the ability of comandra to remain

Figure 17.–Spore-trapping device. A clock drive pulls a series of glass slides on a belt beneath an opening. This trap is equipped with a battery-operated exhaust fan so that air is drawn through a glass tube and particles come in contact with glycerine-jelly-coated glass slides. If the intake tube is replaced by a horizontal slit and the exhaust fan is not used, this device can trap particles that settle by gravity onto sticky slides.

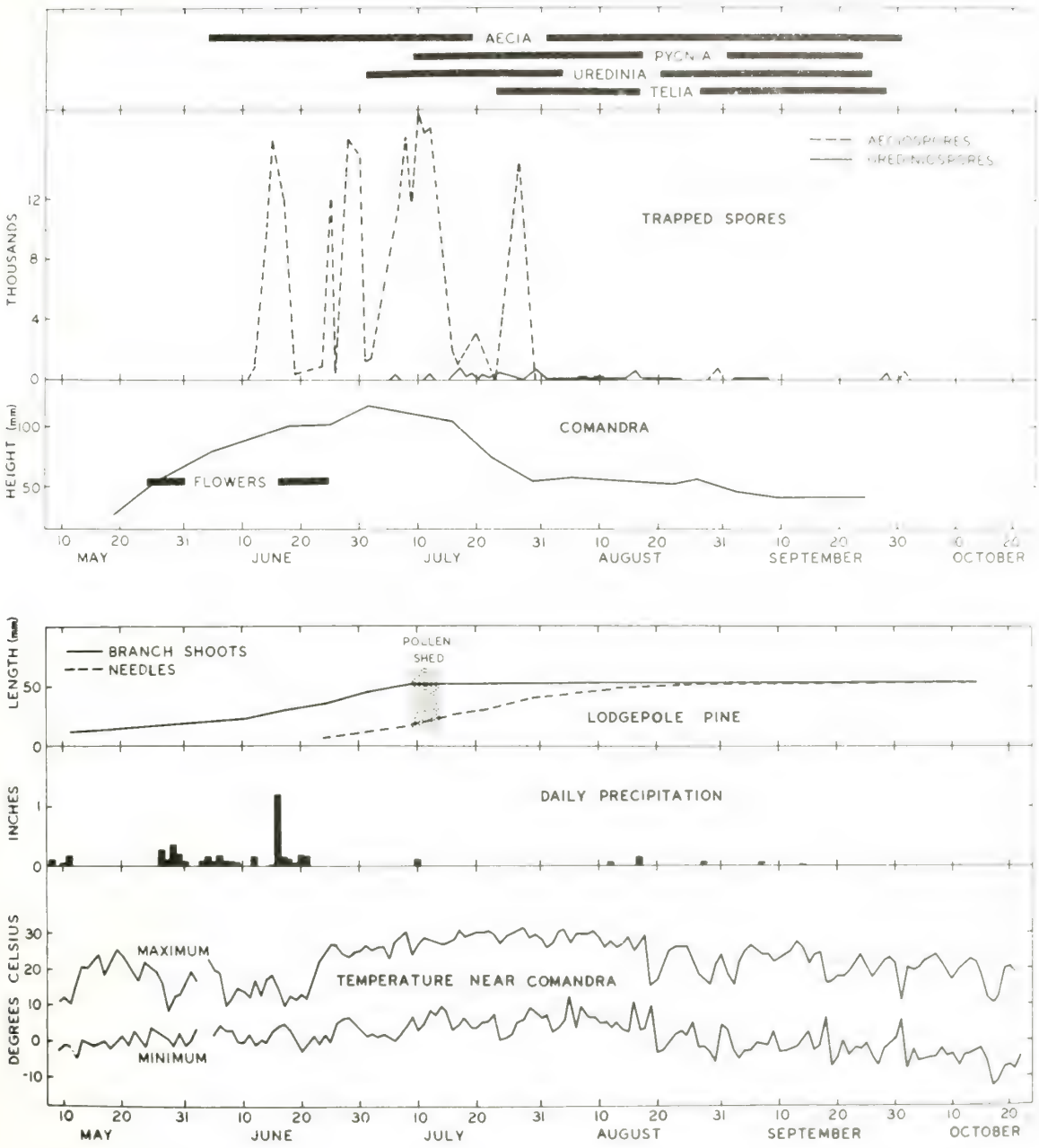

Figure 18.–Phenology of *C. comandrae* and hosts in Beaver Mountain plot in 1964 in response to weather conditions. In these diagrams, the seasonal extent of presence of fruiting bodies, number of spores trapped by gravity, growth of comandra shoots and duration of flowering, and growth of lodgepole pine may be studied in relation to the precipitation and temperature conditions existing during the period May through October.

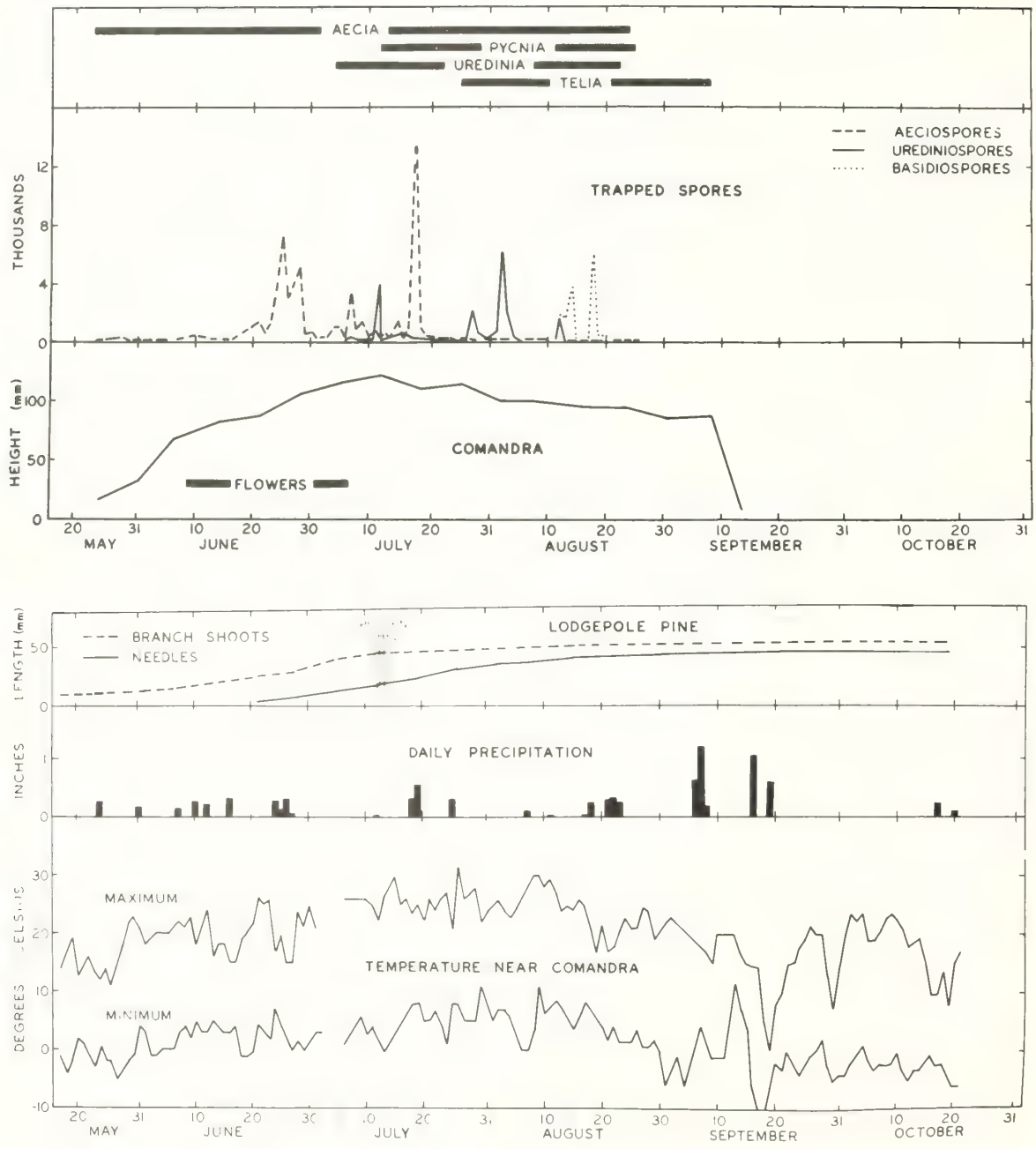

Figure 19.–Phenology of *C. comandrae* and hosts in Beaver Mountain plot in 1965.

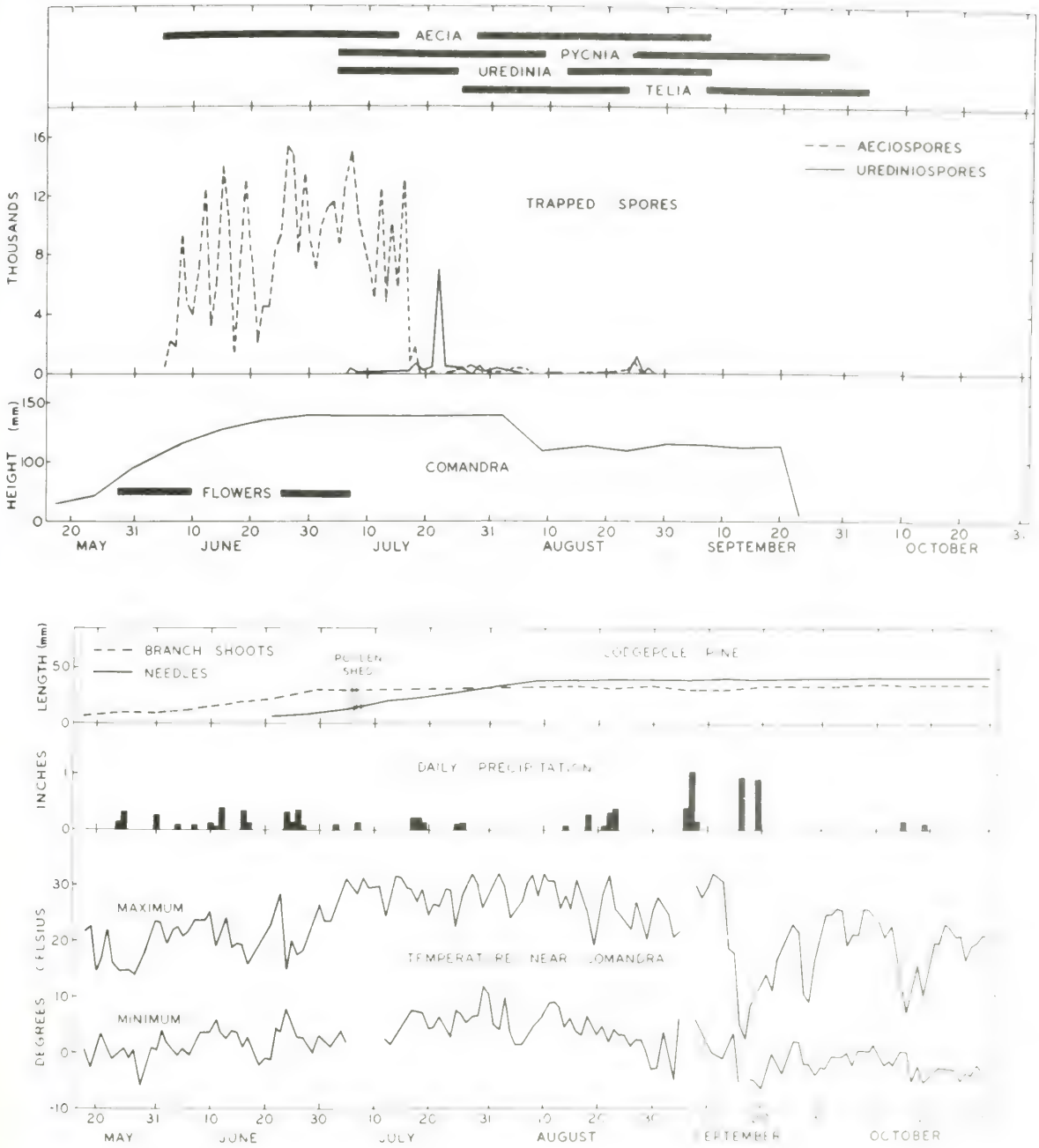

Figure 20.--Phenology of *C. comandrae* and hosts in Fish Haven plot in 1965.

in plant communities near rust-infected lodgepole pine for long periods even though heavily infected by comandra rust almost every year. The combination of susceptible comandra shoots and general rainfall during the period aeciospores are being shed makes conditions suitable for primary infection, as the rust is usually common by mid-July on comandra near infected pine stands. The capability of aeciospores to germinate well at prevailing cool temperatures also enhances primary infection of comandra. By mid-July, aeciospores are reinforced by urediniospores as a source of inoculum. By this time, thundershowers generally prevail and spread becomes more haphazard. Because infection of comandra shoots takes only a short time, thundershowers usually result in some secondary spread. In most years infected comandra can commonly be found a few miles from infected pines, but in 1966, which was drier than normal in July and August, the rust in comandra was rare beyond a few hundred yards from infected pines. Apparently little secondary spread occurred in that year.

Although telia are present from late July until hard frosts in autumn, basidiospores are cast only rarely. Not only were basidiospores rarely trapped, but also visual observations indicated that basidiospore production had seldom occurred. Low temperatures prevent any appreciable cast at night during radiation dew periods even though relative humidity near comandra commonly reaches 100 percent for 4 to 6 hours. Moisture from thundershowers usually does not last long enough to initiate basidiospore casting, but when it does, drying on succeeding sunny days greatly reduces chances of pine infection. By such action the potential of the inoculum may be reduced to the point of limiting infection, even if favorable conditions follow. Therefore, it appears that thundershowers are detrimental to the chances for pine infection.

It seems likely that serious outbreaks of pine infection in the Rocky Mountain States can occur only when large warm storms invade and remain in the area for several days during August or early September when telial inoculum is plentiful and highly viable. As shown in figure 21, heavy rainfall is not necessary for abundant telial germination, but saturated air and long periods of mild temperatures must prevail. Even during those periods when most basidiospores were trapped during these studies (figs. 21 and 22), casting was soon followed by periods of moder-

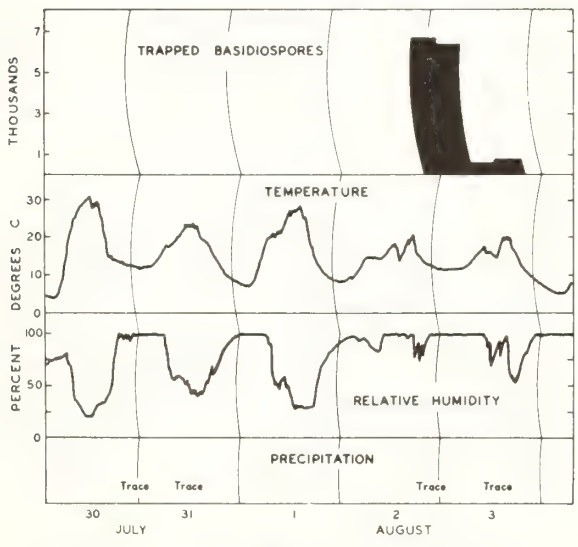

Figure 21.--A successful suction trapping of basidiospores; and the corresponding weather data in Beaver Mountain plot 1966.

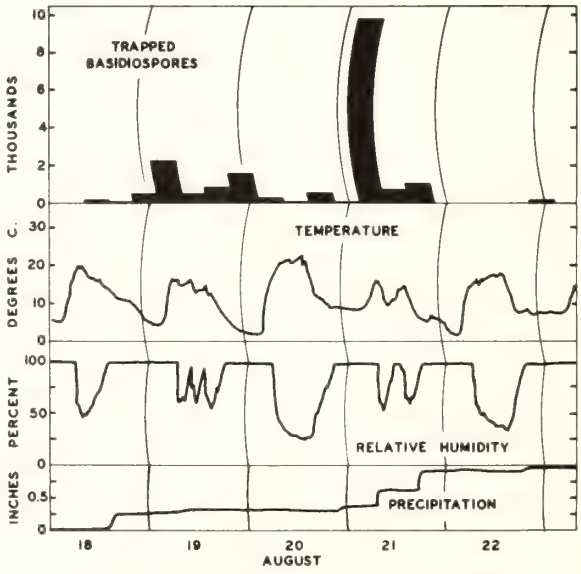

Figure 22.–A successful suction trapping of basidiospores; and the corresponding weather data in Beaver Mountain plot 1965.

ately low relative humidity, and it is doubtful that pine infection could have resulted. In autumn, though longer moist periods associated with frontal storms are again more common, temperatures are probably too cold for basidiospore casting. Thus it seems that weather conditions that could lead to abundant pine infection are rare in the Rocky Mountain States.

Tissue Susceptibility

By the time telia are present on comandra, stems of lodgepole pine have finished elongation and are no longer succulent. This has been taken to indicate that pine infection occurs through needles rather than directly in stems. Whereas results from experimental infection of lodgepole pine and from phenological data indicate that current-year and 1-year-old shoots are probably more susceptible, four young infections found in Teton National Forest in 1966 support a different view. These infections, like those artificially induced, were on needle-bearing stems and had produced about the same degree of swelling; pycnia were exuding apparently for the first time. If we assume that the young trees were infected only 1 or 2 years previously, like the artificially infected seedlings in a similar stage of development, we can conclude that two infections entered 2- or 3-year-old shoots, one a 3- or 4-year-old shoot, and one a 4- or 5-year-old shoot. This apparent contradiction of evidence from my pine infection trials stresses the need for additional information on susceptibility of tissues.

Seasonal Spore Viability

Studies were designed to determine viability of spores collected throughout a growing season. Viability at 18° ±0.5° C. was determined with samples collected from fruiting structures once a week. Aeciospores were tested on collodion films on distilled water and urediniospores and basidiospores on 2 percent water agar; teliospore viability (measured by numbers of basidiospores cast from whole telia) was determined in moist chambers over 2 percent water agar at pH 2. Telia were incubated 72 hours and other spores 24 hours. At least 200 aeciospores or urediniospores were examined in each test for percent germination, and 20 each for length of germ tubes. Percent germination multiplied by mean germ tube length gave an index of germination (trends of both percent and lengths were similar).

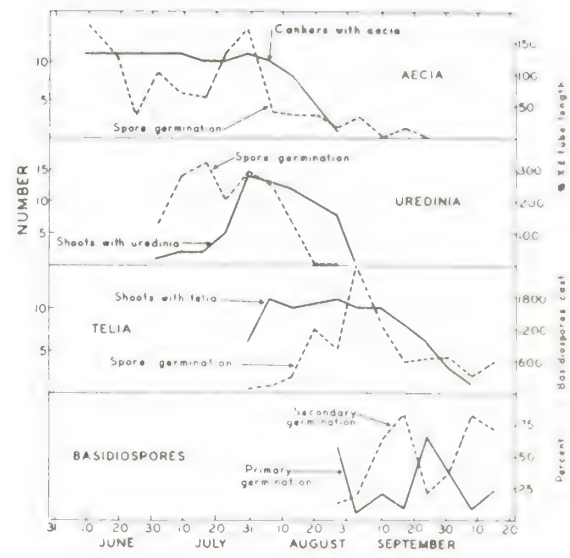

Figure 23.–Prevalence of *C. comandrae* fruiting structures and corresponding viability in Fish Haven plot 1964. In bottom graph, curves are shown for germination by formation of a germ tube (primary) or by production of another basidiospore (secondary).

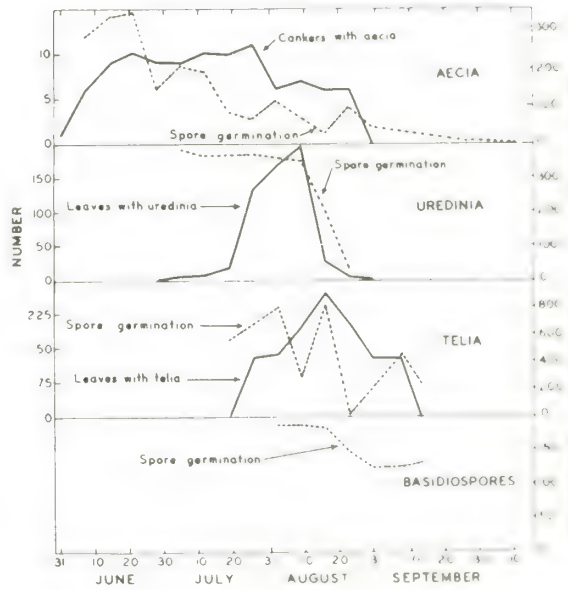

Figure 24.--Prevalence of *C. comandrae* fruiting structures and corresponding viability in Beaver Mountain plot 1965. Since germination of basidiospores during this year was entirely by formation of germ tubes, only one curve is shown.

Viability of aeciospores and urediniospores was highest during June and July and tapered off in mid-August and into September (figs. 23 and 24). Thus the chances of additional comandra infection in late summer and autumn are diminished in two ways–the inoculum is reduced in quantity and the spores are less able to infect comandra because of reduced vigor of germination.

As telia elongate by formation of new teliospores, their ability to cast basidiospores increases, and they become highly viable in early August. Telial viability then decreases irregularly over the rest of the season. Decreases result from occasional germination of teliospores and possibly from aging and daily exposure to near-inhibitory high and low temperatures. New telia and new teliospores continue to form, and the ability of telia to cast basidiospores may again increase somewhat. Viable telia are present until death of the host shoot, even though the number of spores cast is reduced late in the season.

The evidence as to the ability of basidiospores to germinate is more confusing. In general, germination by germ tubes decreased as the season progressed. Sometimes this was because secondary basidiospores were formed rather than germ tubes. Factors thought to influence the type of germination of basidiospores of the conifer rusts include pretreatment of basidiospores (Reed and Crabill 1915 and Spaulding and Rathbun-Gravatt 1926) and environmental conditions during germination (Bega 1960 and Hirt 1935); these did not enter into my experimental results, as conditions during germination tests were held constant and there was no pretreatment of basidiospores.

SUMMARY AND CONCLUSIONS

The rust fungus *Cronartium comandrae* was studied in the laboratory and field to determine how various environmental factors influence the rate of spread of comandra blister rust. *C. comandrae* overwinters and is perennial in cankers in pines. It dies out annually on comandra in the mountains. Activity of *C. comandrae* is thus limited chiefly to the growing season of the hosts.

Aeciospores that form on infected pines are disseminated by wind and infect only comandra plants. Aeciospores may survive several days of fairly severe conditions before losing viability; they germinate when exposed to mild temperatures on moist surfaces. Temperatures from 8° to 18° C. are best for maximum germination and germ tube growth. On comandra, germ tubes develop appressoria, which attach to stomates. From appressoria, infection pegs penetrate between guard cells to infect the plant. Maximum infection occurred in shoots held at 18° C. in mist chambers for 48 hours.

In the field, uredinia develop on comandra leaves and stems about 2 or 3 weeks after infection. By wind dispersal, urediniospores are distributed to other comandra shoots. Urediniospores also retain viability for several days after dissemination even under harsh conditions. In the presence of free water and mild temperatures, urediniospores germinate. Temperatures of about 13° to 23° C. are most favorable for germination and infection of comandra. Like those of aeciospores, germ tubes of urediniospores penetrate through stomates of comandra.

About 4 to 6 weeks after initial infection in the field, telia form on leaves and stems. The telia remain attached to comandra, and only under proper conditions do their teliospores germinate to form basidiospores that are dispersed by wind to infect pines. Teliospores germinate in either darkness or light after exposure to several hours of saturated air at mild temperatures. In unsaturated air telia may remain viable for several weeks. Prolonged exposure to temperatures above 25° C. reduces telial viability, and daily warm temperatures in the mountains probably reduce viability slowly. Freezing temperatures reduce telial viability. After about 6 hours' exposure to conditions favorable to germination, teliospores

begin casting basidiospores. The rate of casting is rapid for about 24 more hours if conditions remain favorable. Teliospores germinate over a range of temperatures of 6° to 24° C., but do best at temperatures from 13° to 23° C.

Basidiospores are easily injured by desiccation. Because they are delicate, effective dissemination of basidiospores is probably limited to only a few miles. Best germination occurs at about 13° to 23° C. Basidiospores derived from fresh telia germinate by means of germ tubes, but those from old telia more frequently form secondary basidiospores. Thus, fresh young telia are probably more effective inoculum for pines. Infection of pines occurs in needle-bearing shoots, but the means and exact site of infection are still unknown. Maximum infection in greenhouse trials occurred in seedlings held 48 hours in mist chambers at 20° C.

Outbreaks of comandra blister rust in lodgepole pine occur only rarely in the Rocky Mountain States because the complex series of climatic and biological events necessary for large-scale infection are seldom satisfied. An abundance of aecial inoculum during rainy June weather results in abundant infection of comandra in most years. Thundershowers in July and August tend to intensify infection by means of uredinia, so that comandra plants near lodgepole pine stands infected with comandra rust generally become heavily infected with this rust. However, despite the presence of large masses of telial inoculum, infection of pine usually does not occur because summer and early autumn weather does not permit it. Thundershowers sometimes provide conditions satisfactory for production and perhaps short-range dissemination of basidiospores, but conditions seldom remain favorable long enough for infection of pines. Extensive outbreaks of pine infection probably occur only when large warm frontal rains invade and remain in the region for several days during summers when there is an abundance of highly viable telial inoculum. Fortunately, this seldom happens in the Rocky Mountain States. By autumn, viable telial inoculum is less plentiful and though frontal storms are more frequent, prevailing temperatures are usually too cool for successful pine infection. While these studies point out the reasons for infrequent outbreaks of comandra rust in lodgepole pine, experience reminds us that when mass infection does occur, damage continues for many years over large areas.

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The development of comandra blister rust of lodgepole pine is related to physical factors of the environment. After the rust has overwintered in pine stems, prevailing conditions of moisture and temperature often permit its spread and intensification on comandra. Later in summer and early autumn, when pine-infecting inoculum is present, dry conditions and unfavorable temperatures limit infection of pines. Although destructive, outbreaks of comandra blister rust are rare in pine stands in the Rocky Mountain States.

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U. S. FOREST SERVICE
RESEARCH PAPER INT-51
1968

NETVSL—A COMPUTER PROGRAM FOR CALCULATION OF TREE VOLUMES WITH INTERIOR DEFECT

by

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NETVSL--A COMPUTER PROGRAM FOR CALCULATION OF TREE VOLUMES WITH INTERIOR DEFECT

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PROGRAM DESCRIPTION

NETVSL is a comprehensive computer program for calculating volume, surface area, and length of tree boles from stem measurements. These measurements can be obtained either from felled trees, or taken by a dendrometer from standing trees. Volume units include cubic feet and board feet (Scribner and/or international 1/4" log scale). Total stem contents (including forks) and merchantable contents are calculated for each of the three kinds of volume units. Merchantable contents are defined by arbitrary stump heights, log lengths, and top diameter limits. Stem diameters for the ends of logs are interpolated between adjacent measured stem sections. Top diameters for volumes in board feet are defined by the criterion of Mesavage.[1] Deductions from volume in cubic feet are calculated from descriptive measurements of interior defect obtained by destructive sampling of felled trees. In addition, cull in board feet could be deducted by user-supplied subroutines that are called in the appropriate sequence during execution of the program.

NETVSL has been used to calculate the net volume of trees destructively subsampled in the course of timber management inventories, and to estimate gross volume through dendrometry of a subsample in lieu of using conventional volume tables. Other uses would include calculation of net volume for mill-scale studies, presale cruises, and local volume table construction. Because the computations produce both the board-foot scale and the associated volume-surface-length contents, the latter system of units advocated by Grosenbaugh[2] can be interpreted in the widely used, but misleading, units of board feet (log scale) until conversion coefficients based on mill-scale studies provide a more meaningful interpretation. When presale cruises include destructive sampling to estimate defect deductions, this program can be used to generate the tree or log data cards for subsequent expansion by sample-estimation formulae to produce net volume, surface, and length for the entire sale.

Tree data obtained by dendrometry of standing trees can be recorded in the same form for processing by either NETVSL or by Grosenbaugh's[3] STX program with only a minor difference in the coding for forked trees. This uniformity should simplify the training of dendrometer operators. However, the two programs are intended for quite different purposes. NETVSL is most useful when data from felled trees are being augmented by additional measurements of standing trees, or when a variety of merchantability standards must be applied to the same tree data.

UNITS OF VOLUME

Nine combinations of volume units and merchantability limits are possible at each run. These include volumes in cubic feet or board feet (Scribner and/or International 1/4" log scale). For each of the three volume units, three sets of merchantability limits can be specified: total tree; fixed top diameter, and arbitrary stump height; or variable top diameter and another arbitrary stump height.

Log lengths for board-foot volume calculations are specified at the user's option. Hence, log scaling diameters, positions of minimum top diameters, and stump heights are located by interpolation among the stem sections for the total tree. Table 1 lists the codes identifying the various combinations of units of measure and merchantability limits. These codes appear in the first column of the sample output in figure 1.

---

[1] Mesavage, Clement. Definition of merchantable sawtimber height. J. Forest. 63(1): 30-32. 1965.

[2] Grosenbaugh, L. R. Some suggestions for better sample-tree measurement. Soc. Amer. Forest. Proc. 1963: 36-42.

[3] Grosenbaugh, L. R. STX--FORTRAN 4 program for estimates of tree populations from 3P sample-tree measurements. U.S. Forest Serv. Res. Pap. PSW-13, 49 pp. 1964.

Coded as in table 1

NETVSL OUTPUT RUN 1 PROBLEM 19 PLOT 99 PAGE 4

TOP/RUN/PROB.NO./PLOT NO./TREE NO./SPECIES/AGE/SEC.NO./LOG LENGTH/HEIGHT/DIAMETER/BARK/GROSS VOL./CULL VOL./NET VOL./SURFACE AREA														
1	1	19	99	306	202	220	1	1.00	1.00	28.97	2.79	4.58	0.31	4.27	7.59
1	1	19	99	306	202	220	2	3.50	4.50	25.72	2.37	14.33	0.91	13.41	25.10
1	1	19	99	306	202	220	3	4.60	9.10	22.46	2.20	14.63	0.86	13.77	29.07
1	1	19	99	306	202	220	4	8.20	17.30	21.94	1.97	22.05	1.67	20.38	47.66
1	1	19	99	306	202	220	5	8.10	25.40	20.28	1.36	19.72	2.10	17.62	44.79
1	1	19	99	306	202	220	6	8.20	33.60	19.98	1.86	18.12	2.12	16.01	43.21
1	1	19	99	306	202	220	7	8.10	41.70	19.08	1.86	16.86	2.13	14.73	41.42
1	1	19	99	306	202	220	8	8.20	49.90	17.58	1.74	15.05	2.28	12.77	39.37
1	1	19	99	306	202	220	9	8.10	58.00	16.86	1.50	13.11	1.89	11.22	36.52
1	1	19	99	306	202	220	10	8.20	66.20	15.24	1.32	11.55	1.47	10.08	34.48
1	1	19	99	306	202	220	11	8.10	74.30	13.38	1.44	9.08	1.67	7.41	30.38
1	1	19	99	306	202	220	12	8.20	82.50	11.88	0.96	7.16	1.68	5.48	27.15
1	1	19	99	306	202	220	13	8.10	90.60	8.94	0.96	4.88	0.88	4.01	22.22
1	1	19	99	306	202	220	14	8.20	98.80	6.90	0.54	2.85	0.45	2.40	17.09
1	1	19	99	306	202	220	15	8.10	106.90	5.28	0.36	1.67	0.18	1.49	12.99
1	1	19	99	306	202	220	16	14.10	121.00	0.0	0.0	0.71	0.05	0.67	9.75
1	1	19	99	306	202	220	16	121.00	121.00	23.70	0.0	176.35	20.64	155.71	468.80
FORM FACTOR= .476 VARIABLE TOP= 0.0 VARIABLE BOTTOM= 0.0 BASAL AREA= 3.064														
3	1	19	99	306	202	220	1	0.0	1.00	28.97	2.79	0.0	0.0	0.0	0.0
3	1	19	99	306	202	220	2	3.50	4.50	25.72	2.37	14.33	0.91	13.41	25.10
3	1	19	99	306	202	220	3	4.60	9.10	22.46	2.20	14.63	0.86	13.77	29.07
3	1	19	99	306	202	220	4	8.20	17.30	21.94	1.97	22.05	1.67	20.38	47.66
3	1	19	99	306	202	220	5	8.10	25.40	20.28	1.36	19.72	2.10	17.62	44.79
3	1	19	99	306	202	220	6	8.20	33.60	19.98	1.86	18.12	2.12	16.01	43.21
3	1	19	99	306	202	220	7	8.10	41.70	19.08	1.86	16.86	2.13	14.73	41.42
3	1	19	99	306	202	220	8	8.20	49.90	17.58	1.74	15.05	2.28	12.77	39.37
3	1	19	99	306	202	220	9	8.10	58.00	16.86	1.50	13.11	1.89	11.22	36.52
3	1	19	99	306	202	220	10	8.20	66.20	15.24	1.32	11.55	1.47	10.08	34.48
3	1	19	99	306	202	220	11	8.10	74.30	13.38	1.44	9.08	1.67	7.41	30.38
3	1	19	99	306	202	220	12	8.20	82.50	11.88	0.96	7.16	1.68	5.48	27.15
3	1	19	99	306	202	220	13	8.10	90.60	8.94	0.96	4.88	0.88	4.01	22.22
3	1	19	99	306	202	220	14	8.20	98.80	6.90	0.54	2.85	0.45	2.40	17.09
3	1	19	99	306	202	220	15	8.10	106.90	5.28	0.36	1.67	0.18	1.49	12.99
3	1	19	99	306	202	220	16	3.60	110.59	3.90	0.27	0.43	0.03	0.40	4.43
3	1	19	99	306	202	220	15	109.59	110.59	23.70	0.0	171.48	20.32	151.17	455.89
FORM FACTOR= .476 VARIABLE TOP= 3.90 VARIABLE BOTTOM= 1.00 BASAL AREA= 3.064														
5	1	19	99	306	202	220	1	0.0	1.00	28.97	2.79	0.0	0.0	0.0	0.0
5	1	19	99	306	202	220	2	16.40	17.40	21.92	1.96	351.40	0.0	351.40	102.41
5	1	19	99	306	202	220	3	16.40	33.80	19.96	1.86	288.63	0.0	288.63	88.47
5	1	19	99	306	202	220	4	16.40	50.20	17.55	1.73	220.16	0.0	220.16	81.13
5	1	19	99	306	202	220	5	16.40	66.60	15.15	1.33	160.83	0.0	160.83	71.21
5	1	19	99	306	202	220	6	16.40	83.00	11.70	0.96	91.76	0.0	91.76	57.48
5	1	19	99	306	202	220	7	6.00	89.00	9.54	0.96	18.58	0.0	18.58	16.76
5	1	19	99	306	202	220	7	88.00	89.00	23.70	0.0	1131.36	0.0	1131.36	417.46
FORM FACTOR= .476 VARIABLE TOP= 9.54 VARIABLE BOTTOM= 1.00 BASAL AREA= 3.064														
8	1	19	99	306	202	220	1	0.0	1.00	28.97	2.79	0.0	0.0	0.0	0.0
8	1	19	99	306	202	220	2	16.40	17.40	21.92	1.96	331.86	0.0	331.86	102.41
8	1	19	99	306	202	220	3	16.40	33.80	19.96	1.86	270.80	0.0	270.80	88.47
8	1	19	99	306	202	220	4	16.40	50.20	17.55	1.73	204.37	0.0	204.37	81.13
8	1	19	99	306	202	220	5	16.40	66.60	15.15	1.33	147.01	0.0	147.01	71.21
8	1	19	99	306	202	220	6	16.40	83.00	11.70	0.96	80.67	0.0	80.67	57.48
8	1	19	99	306	202	220	7	6.00	89.00	9.54	0.96	17.05	0.0	17.05	16.76
8	1	19	99	306	202	220	7	88.00	89.00	23.70	0.0	1051.75	0.0	1051.75	417.46
FORM FACTOR= .476 VARIABLE TOP= 9.54 VARIABLE BOTTOM= 1.00 BASAL AREA= 3.064														

Figure 1.--Copy of printed output for one tree shows log data and tree totals.

Table 1.

Merchantability limits	Cubic feet	Board feet International 1/4" log	Board feet Scribner
Total tree	1	4	
Variable top diameter and fixed stump height	2	5	8
Fixed top diameter and fixed stump height	3	6	9

[1]For total-tree volumes in board feet, an initial top diameter of 4" is assumed and then increased until the volume of the top log is maximized. The stump height for combinations 4 and 7 is assumed to be one-half foot.

Mesavage's definition of merchantable sawtimber height is used for all six combinations involving board-foot scaling units. That is, the program interpolates to find the location of the minimum top diameter specified by the user. Then the length of the topmost log is reduced in successive intervals of 2 feet so long as the volume of the piece is increased thereby, or until the length of the top log has been reduced to 6 feet. The top diameter as finally established by this analysis is printed and/or punched with the tree totals. However, for forked trees, only the top diameter of the last fork is displayed.

FORM OF OUTPUT

All tree identification and the computed volume, surface, length, and defect volume data can be printed, punched into cards, or both, for each measured or interpolated section in the tree. However, the data for separate sections can be suppressed in either type of output, so that tree totals only would be printed as in figure 1 or punched into cards. In addition, totals of all the trees in each plot and in each problem can be printed at the user's option. Figure 1 is an example of the printed output for one tree showing both the dimensions of the separate sections, and the tree totals. Output data for log lengths and heights are in feet; diameters and double bark thicknesses are in inches; and surface area and basal area are in square feet.

Format of the punched output follows the sequence of the printed output with three exceptions. First, the number of forks is punched in column 80. Second, section and log detail cards have a "1" punched in column 79 that is replaced by a "2" on tree-total cards. Third, coding for grade of the piece replaces form factor on the section detail cards for cubic-foot volume units (i.e., those coded 1, 2, or 3 in column 1).

Location and identification of the output fields are indicated below:

Item	Column	Format
Units and merchantability limits (see table 1)	1	I1
Run number	2-5	I4
Problem number	6-8	I3
Plot number	9-11	I3
Tree number	12-15	I4
Species	16-18	I3
Age	19-21	I3
Section number	22-23	I2
Section length	24-28	F5.1
Height	29-33	F5.1
Diameter	34-37	F4.1
Bark thickness	38-41	F4.2
Gross volume	42-48	F7.2
Cull volume	49-55	F7.2
Net volume	56-62	F7.2
Surface area	63-69	F7.2
Form factor	70-73	F4.3
or grade	71-72	A2
Top diameter for tree	74-78	F5.2
Code for detail or total	79	I1
Number of forks in tree	80	I1

TREE DATA USED

For Identification

Six items identify the computed data for each tree. On the printed output these are labeled as RUN, PROB. NO., PLOT NO., TREE NO., SPECIES, and AGE. The first pair can be varied if more than one set of calculations is needed from a particular collection of tree data. The last four items are directly associated with the original tree data. Although their names are suggestive, in a specific context their meanings are arbitrary. For example, if the trees had been measured during a 3P cruise (Grosenbaugh[3]) the last four variables might represent sale identification, tree number, stratum, and KPI, respectively, and the output headings would be changed accordingly.

For Gross Volume, Surface, and Length

Tree data needed for computation of gross volume in cubic feet consist of a sequence of diameters and either lengths of intervening portions[4] or cumulated length from the base of the tree. These measurements may be obtained by tape or caliper measurements of felled trees, or by optical dendrometer measurements of standing trees. At each fork, a section should be measured below the fork on the main stem, and a fork code associated with this section. Another section is recorded immediately above the fork on the main bole, and measurements on up the main bole are continued to the top, with positions of succeeding forks recorded in the same way. When the top of the main bole is reached, the sequence continues up the boles of each preceding fork starting with a section just above the crotch. Multiple forks should be measured and recorded in a sequence such as is diagramed in figure 2.

---

[3] Grosenbaugh, L. R. STX--FORTRAN 4 program for estimates of tree populations from 3P sample-tree measurements. U.S. Forest Serv. Res. Pap. PSW-13, 49 pp. 1964.

[4] When diameters and intervening lengths are recorded, the diameter at the top of the section is associated with the length of the section.

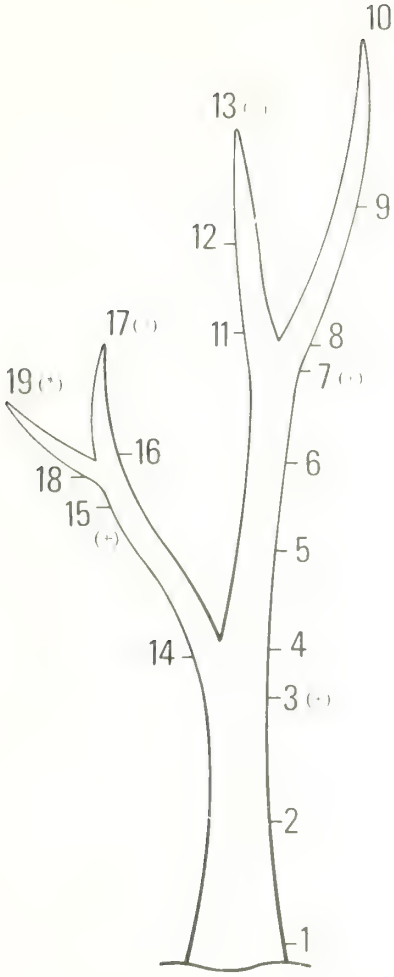

Figure 2.--Sequence of measurements for forked trees.

If merchantable top specifications include bark and the volume is specified to be inside bark, then the bark thickness should be measured or estimated. If bark thickness is to be estimated by an equation, the calculation can be done in a user-supplied subroutine, BARKEQ, described later in this paper. The intervals between the diameter measurements are arbitrary. However, diameters at abrupt changes of taper should be recorded because scaling diameters for board feet are interpolated for a position corresponding to the top of each log of nominal length plus trim allowance.

For Defect Volume (Cubic Feet)

Defect is recorded from measurements taken on cut sections. As many as three separate areas of defect can be identified on each section. Because it is necessary to associate the cull areas on succeeding sections, these vertically associated measurements will be referred to as cull columns. Three measurements are used to describe the cross section of each cull column. The first two are dimensions, and the third is a letter describing the shape of the cross section. This latter information is the key to how the dimensions are combined to compute the cross-sectional area of the cull

column. The five shapes[5] for each cull cross-section are coded as follows: (1) rectangular (R), (2) circular (C), (3) elliptical (E), (4) pie-shaped (P), and (5) annular (A).

For Grade Classification (Cubic Feet)

A grade may be assigned to each portion of the tree between measured diameters. The grade can be any two-character alphanumeric code.

COMPUTER REQUIREMENTS

The program is written in FORTRAN IV (IBSYS) for operation on the IBM 709X series, and in FORTRAN IV (G or H level) for operation on IBM System 360 computers. It uses three logical input-output units corresponding to the functions of card reader, printer, and card punch. Storage required on the IBM 709X series computers is about 16,000 words, and on the IBM System 360 model 67 about 65,000 bytes are used. These requirements do not include the input-output subroutines.

Source decks of this program may be obtained from the authors.

PREPARATION OF DATA FOR INPUT

Input to the program consists of a preliminary set of five control cards that identify the run and select options for the final problem, followed by the cards containing the tree data for the first problem. Subsequent problems would each consist of four control cards followed by the corresponding tree data.

Tree data are entered into the computer memory through the subroutine READIN. Two versions of this subprogram are supplied with the program, one for entering data from felled trees, and the other for entering dendrometry data. Specifications for tree data to be read by one or the other of these versions are given below. However, the user may wish to revise the READIN subprogram to suit his specific needs. Information to help a programer revise READIN is provided later in this paper.

SELECTION OF OPTIONS

A run consists of all data processed at one execution of the program. A run may consist of one or more problems, which are in turn divided into plots. One card selects certain options for the entire run. Three cards for each problem select input-output options and specify units, top limits, stump heights, log lengths, and data format. Finally, a card heading each set of plot data determines the plot summary option.

The format for each of these five option cards and the function each field serves are indicated below:

Option	Value	Column	Name	Format
RUN OPTION CARD				
Run number	xxxx	1-4	IAPNO	I4
Print a combined summary of all problems?	Yes = 1 No = 0	6	IAPSUM	I1

[5] The coding provides for 10 shapes, but is now implemented for only these five shapes.

Option	Value	Column	Name	Format
PROBLEM OPTION CARD (1)				
Problem number	xxxx	1-4		
Print a summary of all trees in problem?	Yes = 1 No = 0			I1
Logical number of input unit[6] for tree data	x			I1
Logical number of output unit[6] for printing	x	10		I1
Logical number of output unit[6] for punching	x	12		I1
Diameters are recorded in	Inches = 0 Feet = 1	14		I1
Height defined by summing piece length	IFHT = 0	16		I1
Height defined as distance from ground to top of section	IFHT = 1			
Compute bark thickness in subroutine BARKEQ?	Yes = 1 No = 0	18		I1
Compute defect? If so, what are the units in which it is measured?	No cull = 0 Inches = 1 Feet = 2	20	IFCL	I1
Will cull codes be used?	Yes = 1 No = 0	22		I1
Will fork codes be used? If so, what character indicates a fork?	No = Blank Yes = Nonblank Character = Nonblank	24		I1
Will debugging output be printed?	Yes = 1 No = 0	26	IDBUG	I1
Print cubic-foot measurements?	No = 0 Tree only = 1 Log & tree = 2	28		I1
Punch cubic-foot measurements?	No = 0 Tree only = 1 Log & tree = 2	30	IOCFP	I1
Print board-foot measurements?	No = 0 Tree only = 1 Log & tree = 2	32		I1
Punch board-foot measurements?	No = 0 Tree only = 1 Log & tree = 2	34		I1
Log length (nominal) in feet	xxx.xx	36-38		F5.2
Trim allowance for logs	xxx.xx	40-44		F5.2

[6] If logical units for input/output are not defined here, the logical unit numbers will be set to the default values contained in the BLOCK DATA subprogram.

PROBLEM OPTION CARD (2)

Calculate cubic-foot volume for total stem?	Yes = 1 No = 0	4	INTC	I1
Fixed top in inches multiplied by 10 for merchantable volume in cubic feet	xxxx	5-8	IVTFC	I4
Stump height (feet) multiplied by 10 to accompany fixed top for cubic feet	xxxx	9-12	IVBFC	I4

NOTE: If either IVTFC or IVBFC is greater than zero, cubic-foot volume to a fixed top will be calculated.

Percent of d.b.h. (o.b.) to be used for variable top for cubic feet in subroutine VARTCF.	xxxx	13-16	IVTPC	I4
Stump height in feet multiplied by 10 to accompany variable top for cubic feet.	xxx	17-20	IVBPC	I4

NOTE: If either IVTPC or IVBPC is greater than zero, cubic-foot volume to a variable top will be calculated.

Calculate board-foot volume for entire stem to 4" top?	Yes = 1 No = 0	24	INTB	I1
Fixed top in inches multiplied by 10 for board feet	xxxx	25-28	IVTFB	I4
Stump height in feet multiplied by 10 to accompany fixed top for board feet	xxxx	29-32	IVBFB	I4

NOTE: If either IVTFB or IVBFB is greater than zero, board-foot volume to a fixed top will be calculated.

Percent of d.b.h. (o.b.) to be used for variable top for board feet in subroutine VARTBF.	xxxx	33-36	IVTPB	I4
Stump height in feet multiplied by 10 to accompany variable top for board feet.	xxxx	37-40	IVBPB	I4

NOTE: If either IVTPB or IVBPB is greater than zero, board-foot volume to a fixed top will be calculated.

Log rule for board feet	INT 1/4=0 Scribner = 1 Both = 2	44	INORSC	I1
Variable top for cubic-foot volume is measured outside bark?	Yes = 1 No = 0	48	IDOPPC	I1
Fixed top for cubic-foot volume is measured outside bark?	Yes = 1 No = 0	52	IDOPFC	I1

Option	Value	Code	Name	Col.
PROBLEM OPTION CARD (2	con.)			
Variable top for board-foot volume is measured outside bark?	Yes = 1 No = 0			
Fixed top for board-foot volume is measured outside bark?	Yes = 1 No = 0			

FELLED-TREE FORMAT CARD (for [illegible] CARD for dendrometry data)

FORTRAN input format enclosed in parentheses				

PLOT OPTION CARD

Plot number (must be nonblank and nonzero)	XXXX			
Print a summary of all trees in the plot?	Yes = 1 No = 0	6	IPLSUM	11

The options selected for each problem are described on the first page of the computer-printed results for each problem (fig. 3). For cross-referencing, the names and values of the variables cuing each line have been superimposed on the output.

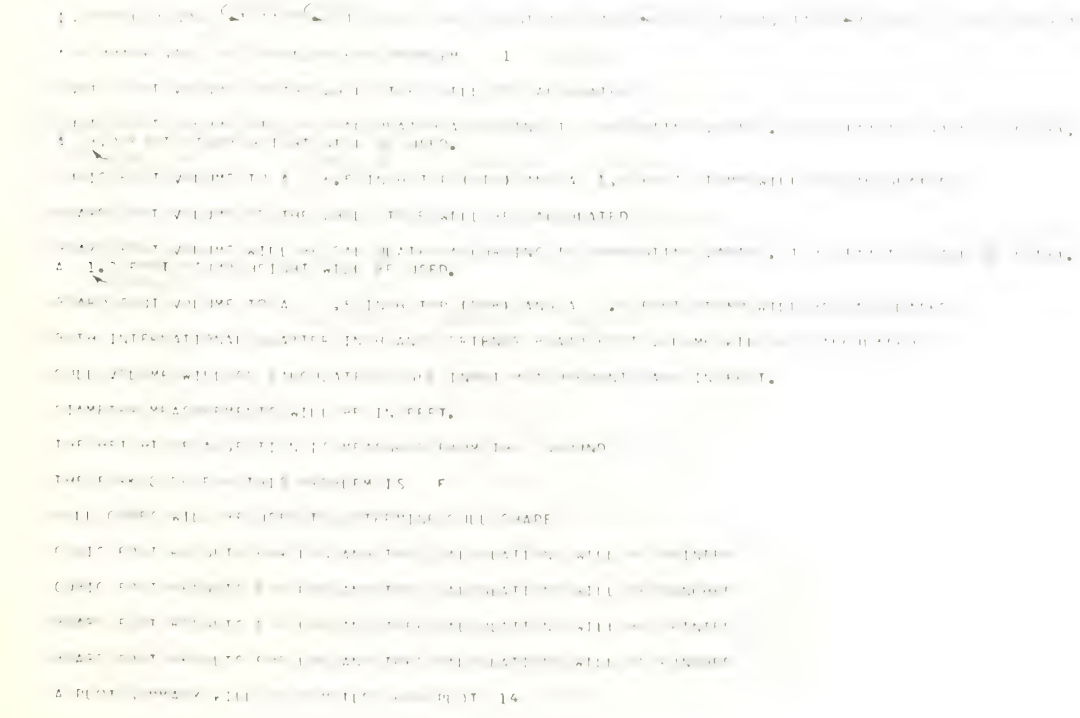

Figure 3.--Copy of first page of printed output listing the options selected for problem 1. Values of variables cuing each line have been superimposed on the listing.

DATA FROM FELLED TREES

Data for each cut section are obtained from cards sorted into sequence beginning at the base of the tree and proceeding up the stem. The format of these cards is specified on the PROBLEM FORMAT CARD. However, the data sequence required by the felled-tree version of the subroutine READIN included with the program is as follows:

Plot number Tree number Species D.b.h. Age	Same for all sections in one tree.
Height	Height above ground or length of piece.
D.o.b. D.o.b.	Outside bark diameters of upper end of the section.
D.i.b. D.i.b.	Inside bark diameters of upper end of the section.
DBT	Double bark thickness.[7]
W1	1st cull dimension of 1st cull column.
B1	2nd cull dimension of 1st cull column.
J1	Shape code of 1st cull column.
W2 B2 J2	As above for 2nd cull column.
W3 B3 J3	As above for 3rd cull column.
BW BB JB	Data to be transmitted to user-supplied subroutine to calculate board-foot deductions for defect.
IFORK	A fork indicator here means that a fork leaves the bole at this level.
IG	Grade of piece below the measurement level.

The units of measure and other alternatives for the above data depend on the options selected by the appropriate punches on the first problem option card, which was described under the heading "Selection of Options." In the above list, plot number, tree number, species, and age are treated as integer data in the computer program. J1, J2, J3, JB, and IG are treated as alphanumeric data. The remaining variables are stored as floating-point data.

DENDROMETRY DATA FROM STANDING TREES

Gross volumes of trees measured with an optical dendrometer can be computed with the same options by replacing the felled-tree version of the READIN subroutine with the corresponding dendrometry version of READIN. This latter program accepts tree data measured and punched to the specifications used in Grosenbaugh's STX program with the

[7] DBT does not need to be recorded if it is adequately described by D.o.b. minus D.i.b.

exception of the slash (/) for tops of forked trees. However, the tree extrapolation options provided in STX are not used in NETVSL. Instead, the total height of the stem should be measured so that interpolation of the unseen bole can be accomplished.

Dendrometer constants B, Q, U, and G are entered on a DENDROMETER CONSTANT CARD that replaces the PROBLEM FORMAT CARD in the felled-tree data sequence. For definition of these constants and for their format, refer to the second STX control card, which can be used unchanged for NETVSL.

Tree data are entered on two types of cards: a tree input card and subsequent dendrometer input cards. Corresponding variable names in the two programs for the variables on these cards are as follows:

NETVSL	Column	STX
TREE INPUT CARD		
ID	1-4	[illegible]
XJ	5	J
IAGE	6-9	[illegible]
ITYPE	10	LST
Not used	11	XCERT
Not used	12-16	BETATH (CLASS)
DBH	17-21	[illegible]
Not used	22-26	Tree options
XBKA	27-30	[illegible]
XBKB	31-34	BKB
Not used	35-76	Extrapolation data
XJOB (Plot no.)	77-80	[illegible]
DENDROMETER INPUT CARD		
ID	1-4	[illegible]
XJ	5	J
TGRADS	12-15	TGRADS
FGRADS	16-19	FGRADS
SINELV	20-24	SINELV
IG	25-26	GAMATH
TGRADS	27-30	TGRADS
FGRADS	31-34	FGRADS
SINELV	35-39	SINELV
IG	40-41	GAMATH
TGRADS	42-45	TGRADS
FGRADS	46-49	FGRADS
SINELV	50-54	[illegible]
IG	55-56	GAMATH
TGRADS	57-60	TGRADS
FGRADS	61-64	FGRADS
SINELV	65-69	SINELV
IG	70-71	GAMATH
XTERM	72	[illegible]
XJOB	77-80	Identification

The variable XTERM is used by NETVSL somewhat differently than its counterpart in STX. A blank value for XTERM indicates that the current dendrometer card is filled, and more measurements are to be found on the subsequent card. An asterisk indicates the last dendrometer card for a specific tree. A plus sign in XTERM indicates that the last trio of dendrometer measurements was taken at the point where a fork was

encountered. Subsequent dendrometer measurements will continue for this tree on the next card. The tip for each fork *except the last* is indicated by a slash (/) in XTERM of the last card containing data for that fork.

Dendrometry of the two lowest measurement levels may not be feasible. Accordingly, NETVSL follows the STX procedure[8] for substituting tape-measured diameters and lengths. Initial TGRADS should be recorded as a fictitious -999. Then initial FGRADS should be the stump diameter outside bark, in inches and tenths. The corresponding SINELV should be the length between stump top and the next measurement level, recorded in feet and tenths with the decimal point punched. Second TGRADS should be blank, while second FGRADS should be the diameter at the next measurement level (usually b.h.). Second SINELV is recorded as length (in feet and tenths with decimal point punched) between this measurement level and the first actually dendrometered measurement level above. Examples to illustrate these procedures are provided in appendix A.

TERMINATING PROCEDURE

Transition from cards containing data for one tree to cards for the next tree is indicated by the change in tree number (felled-tree data) or by the terminal asterisk (dendrometry data). The end of a plot is indicated by a blank card. That is, a blank card will suffice so long as the preceding tree number is nonzero.

A second blank card indicates the end of a problem, and a third blank card terminates the run.

CALCULATION PROCEDURES

GEOMETRIC ASSUMPTIONS

Tree Bole

Wood volume and surface area below the first diameter measurement are computed as though the stump were a cylinder of the given length and diameter. The diameter of the uppermost section of each fork must be zero. If the field measurements do not include the tip of the tree, a fictitious section of trivial length and zero diameter will suffice to permit computation to proceed. No attempt will be made to extrapolate beyond the actual measurements. The volume, area, and any interpolated diameters in the section terminating at the tip are computed as though the section were a right cone. Intervening sections of normal taper are treated as right parabolic frustra. Hence, their volume in cubic feet is computed by Smalian's formula, and the surface area as the surface of revolution of the appropriate parabolic segment. If the diameter at the top of a section exceeds the next lower diameter, the intervening section is treated as an inverted right conic frustrum.

Cull Columns

For each cross section, the area of each cull column is computed by the equations shown in table 2 associated with their respective shapes, the dimensions W and B of the cull column cross section, and the bole diameter, D. The volume in cubic feet of a cull column between two succeeding sections is computed by assuming the following geometric shapes having the indicated end areas.

[8] This description is paraphrased from the comments in SBR subroutine written by L. R. Grosenbaugh.

Table 2.--

Shape	Code
Rectangular	R
Circular	C
Elliptical	E
Pie-shaped	P
Annular	A

[1]S is measured in square feet. W and B will be converted to feet if cull is specified to have been measured in inches.

(1) A frustrum of a right paraboloid when the defect is visible on both ends of the log.

(2) A right paraboloid tangent at its vertex to the lower end of the portion when the cull is visible only on the cut surface of the upper end.

(3) A right cone with vertex at the upper cut if the cull is visible only on the lower cut surface of the piece.

Inaccurate calculation of volume and surface will result if the tree does not conform to the above abstractions. However, the magnitude of the error can be reduced by closer spacing of the section measurements. If the above assortment of cull shapes does not adequately approximate the cull area, the shape should be designated as R, the first dimension set equal to the true cull area, and the second dimension set equal to 1.

SUBPROGRAMS INTENDED TO BE MODIFIED OR SUPPLIED BY THE USER

The NETVSL program calls several subprograms to perform certain calculations that users may have reason to modify for local conditions or to meet specific objectives. These subprograms are:

(1) READIN, that transfers data from the card (or tape) source into the appropriate storage location for the variables needed for computation.

(2) BARKEQ, that calculates bark thickness.

(3) VARTCF, that calculates the variable top diameter for cubic-foot volume (output code 2).

(4) VARTBF, that does the same for board-foot volume (output codes 5 and 8).

(5) BRDCUL, that calculates the defect deductions for net board-foot volume.

(6) BLOCK DATA, that establishes values of many variables governing input-output unit assignments, and other constants used throughout the program. Details concerning these subprograms follow.

READIN

Two versions of READIN have been programed: one for felled-tree data and one for dendrometry data. READIN is called in three ways. The value of the variable ISET indicates the way in which READIN has been called. READIN is called once per problem with ISET=1 to perform initialization such as reading in variable formats, once per plot with ISET=-1 to read data needed to initialize the program for plot data, and with ISET=0 to read data for subsequent trees in the plot.

The task of the READIN is to enter data into the matrices Z and IZ. These matrices will have as many rows as there are measured sections in the tree. The columns are defined as follows:

```
Z (I,1)  = diameter
Z (I,2)  = height above ground or piece length
Z (I,3)  = W for 1st cull column
Z (I,4)  = B  "   "   "     "
Z (I,5)  = W for 2nd cull column
Z (I,6)  = B  "   "   "     "
Z (I,7)  = W for 3rd cull column
Z (I,8)  = B  "   "   "     "
Z (I,9)  = Double bark thickness (only if measured on tree)
Z (I,10) = Optional use for board-foot defects
Z (I,11) =    "      "   "    "      "     "
Z (I,12) =    "      "   "    "      "     "
IZ(I,1)  = Shape indicator for 1st cull column
IZ(I,2)  =   "       "      "  2nd  "     "
IZ(I,3)  =   "       "      "  3rd  "     "
IZ(I,4)  = Fork indicator
IZ(I,5)  = Optional use for board-foot defects
IG (I)   = Grade of the piece
```

In addition, values should be assigned to the following tree variables:

```
ID       = tree number
DBH      = tree diameter, outside bark
IAGE     = data to be listed as "age." Use is arbitrary.
ITYPE    = data to be listed as "species." Use is arbitrary.
```

In the above list, Z is a matrix of real variables; IZ and IG are alphanumeric variables; ID, IAGE, and ITYPE are integer variables; and DBH is a real variable.

When the dendrometer version of READIN is used, set IFFT=0, IFHT=1, and IFORKI=+ on PROBLEM OPTION CARD (1).

BARKEQ

This subprogram is called from the DIALEN subprogram. It deducts estimated bark thickness from the diameters in the sequence in which they have been stored by DIALEN. The call to this subprogram is bypassed if IFBK (column 18 on PROBLEM OPTION CARD (1)) is zero. The version of BARKEQ distributed with NETVSL estimates double bark thickness

relation:[9]

in which

DBT = double bark thickness
D(I) = outside bark diameter at the level for which bark is being estimated.
DBH = diameter outside bark at breast height (B.H.)
BARKBH = double bark thickness at B.H.
QUAN,DENO = constants establishing the asymptote of the hyperbola, such that DENO-1.=QUAN.

Additional variables available to BARKEQ that are useful for estimating bark thickness are:

ITYPE--the species code
IAGE--the tree age
HT(ITDIA)--the height of the top of the tree
HT(I)--the height at the estimation point

VARTCF

This subprogram calculates the top diameter to be used with output code 2. The version of VARTCF distributed with NETVSL calculates the variable top as a fraction of DBH. The fraction is obtained from IVTPC/100. The latter variable is input data from columns 13-16 of PROBLEM OPTION CARD (2). The argument list with which VARTCF is called is (DBH, IVTPC/100, IVTFC/IVTFLT, VT).

IVTPC and IVTFC are read from PROBLEM OPTION CARD (2). IVTFLT is a scale factor set to 10 in BLOCK DATA. VT is the calculated variable top. Although IVTFC is available, it should be used with caution because a nonzero value of IVTFC will cause calculation of volumes in cubic feet to this fixed top diameter (output code 3 in table 2).

VARTBF

This subprogram is analogous to VARTCF except that it uses IVTPB and IVTFB in the second and third calling arguments. A similar caution applies to using the third argument.

BRDCUL

Defect deductions in board-foot units have not been programed because the rules for these deductions are quite variable. However, the NETVSL program does provide for reading the necessary data and transmitting these data to the BRDCUL subprogram, which is called after log intervals, diameters, and gross volumes have been calculated.

The data for computing cull in board feet are stored in locations identified by the following names:

IBOTM(J)	Index of the data for the bottom section of the Jth fork
ITOP(J)	Index of the data for the top section of the Jth fork

[9] Clement Mesavage (personal communication) has found that this formulation of the vertical trend of bark thickness has wide generality with QUAN=1, DENO=2.

KFORK	Number of forks (equals unity for single-boled trees)
HT(I)	Height above ground
DIA(I)	Diameter in inches
Z(I,10), Z(I,11), Z(I,12)	Board-foot cull dimensions at the *I*th section
IC(I,5)	Shape code for board-foot cull calculations

(For the above variables, I ranges from IBOTM(J) to ITOP(J).)

NOS	Number of logs (plus one for the base of each fork) in the tree
BHT(K)	Height above ground of log top
BDIA(K)	Diameter at top of the log
BFLN(K)	Length of log
BBARK(K)	Bark thickness
BFVS(K)	Board-foot volume (Scribner)
BFVI(K)	" " " (International)
BCLVS(K)	" " " in cull (Scribner)
BCLVI(K)	" " " " " (International)

(For the above variables, K ranges from 1 to NOS.)

BLOCK DATA

Input-output variables are preset in BLOCK DATA to correspond to the system configuration at particular computer centers. The logical units used for I/O are defined by the following self-explanatory variable names: NREAD, NWRITE, and NPUNCH. The number of lines per printed page is set to 60 as the value for the variable LINEC.

Cull codes of C, R, E, P, and A are established in the vector ICLC. The length of ICLC is given by the value of NCODE. The sequence of cull codes should correspond to the sequence implied in the computed GO TO statement in subprogram CUAREA.

Samples of field procedures [illegible] NETVSL may be helpful to some users of this program. These procedures have been developed for use under certain of the programed options, and according to decisions on standards of accuracy that were appropriate for the immediate purpose of a particular analysis. Hence, many of these procedures are more restrictive than the program requires. For instance, the opportunity for grade classification is not used explicitly in either example shown below. When questions arise in interpreting these sample instructions, the answers should be sought in the main body of this paper.

The following examples also contain useful test data for new users of NETVSL.

FELLED-TREE DATA SHEET FOR GROSS AND CULL VOLUME

Location no. 113 Tree no. 501 National Forest C14 Date July 8, 196-

Height above ground	Cubic volume data: DOB 1	DOB 2	DIB 1	DIB 2	DBT	1st cull area: W	B	S	2nd cull area: W	B	S	3rd cull area: S
1.0	363	363			045							
4.5	180	180	158	129	030	18	01	0				R
9.1	166	166	148	125	014	20	01	5				R
* 17.3	148	145	138	116	008	16	02	0				R
25.4	139	136	129	128		10	01	0				R
* 33.0	134	133	123	129		02	00	0				R
37.6	131	130	121	125								
41.7	128	127	122	118								
* 49.9	126	126	116	117								
58.0	123	123	113	113								
* 66.2	110	113	103	106								
74.3	102	106	098	099								
* 82.5	095	096	086	085								
90.6	080	081	072	076								
* 98.8	066	066	055	059								
106.9	048	051	043	045								
~~115.1~~												
~~123.2~~												
128.0	000	000	000	000								
* 131.4												

in two at 4 feet and found that to be

Figure 4.--Sample field sheet for recording felled-tree data.

Instructions for Measuring and Recording Data--Felled Trees (Example 1)

A sample field record sheet with data entered is shown in figure 4. The first five columns record the heights above ground at which measurements were taken. Heights that mark the scaling end of 16-foot logs are preceded by asterisks.[10] All data recorded on the same line as any given height are measurements taken at that height.

Proceeding from left to right across the page, under the heading DOB of Cubic Volume Data, record the long and short diameters of the tree trunk outside bark. Columns headed 1 and 2 are provided for these entries. Under DIB are recorded the long and short diameters inside bark. In trees where double bark thickness cannot be accurately obtained by subtracting average DIB from average DOB, enter double bark thickness under DBT. When this is not necessary, leave DBT blank.

Space is provided for recording measurements from three cull areas in the cross section of the tree (fig. 5). For the First Cull Area, enter under W the width of

FELLED-TREE DATA SHEET FOR GROSS AND CULL VOLUME

Location no. 099 Tree no. 306 National Forest 014 Date JULY 7, 1965 Species 202 DBH 237

	Height above ground	Cubic volume data: DOB 1	DOB 2	DIB 1	DIB 2	DBT	1st cull area: W	B	S	2nd cull area: W	B	S	3rd cull area: W	B	S
	1.0	240	292	220	265		070	056	E	← From 1st rot column					
	4.5	200	274	243	189		061	035	R						
	9.1	240	176	215	163		052	031	R						
*	17.3	210	189	191	175		047	027	R	040	038	E			
	25.4	188	173	172	166		031	013	R	060	041	E	032	015	E
*	33.6	183	181	169	164					053	036	R	039	022	E
	41.7	175	174	159	159		From 2nd rot column →			042	027	R	043	036	R
*	49.9	162	160	146	147					018	022	E	060	043	R
	58.0	153	153	140	141								057	042	E
*	66.2	136	140	124	130								054	040	E
	74.3	125	122	111	112		036	028	E				052	040	E
*	82.5	104	110	098	100		039	030	E				034	028	E
	90.6	083	082	075	074		030	025	R						
*	98.8	063	061	059	056		025	014	R				From 3rd rot column		
	106.9	047	047	044	044		014	009	E						
*	~~115.1~~ 121.0 ~~123.2~~	000	000	000	000	←				4th rot column					
*	~~134.4~~	Heading knot [illegible] top of the tree													

Figure 5.--Sample field recording sheet for a tree having four columns of interior defect.

[10] Implicit in these heights are the options on stump height, log length, and trim allowance.

the cull area. Under B enter the breadth of the cull area. Under W enter the width and breadth mean the long and short measurements of the cull area. Under S indicate the shape of figure most closely approximating the cull area. For an ellipse (including a circle) enter E. For a rectangle (including a square) enter R. For ring-shaped defect, the outer and inner dimensions of the ring are recorded under W and B respectively, and "A" is the shape code (fig. 6).

Pie-shaped defect affecting an entire segment of the cross section can be recorded by "P" for shape. Then, W/B is the fraction of the circle to be deducted.

If called for, the procedure outlined for the First Cull Area will be repeated for the Second Cull Area and/or the Third Cull Area.

More than one rot column can be recorded under First Cull Area if there is at least one intervening measured section with no entry in that column.

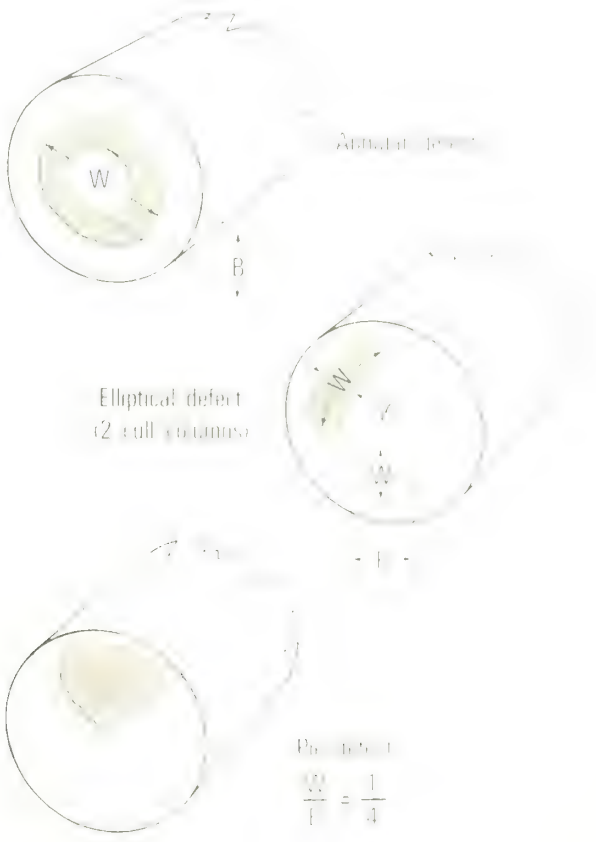

Figure 6.--Cull shapes and corresponding measurements to describe them.

The same instruction applies to a second or third rot column, if encountered. For example, suppose that a single rot column extends from the stump upward into the tree bole. Designate cross sectional areas of this rot column as the First Cull Area. When a second rot column is encountered, as shown in figure 5, its measurements will be recorded under Second Cull Area. The same would be done for a third rot column. When the first rot column runs out, do not shift columns on the data sheet. Data for a continuous rot column in the tree must be recorded entirely under one cull area column. Continue to record measurements of the second rot column under Second Cull Area until it runs out. Do likewise for the third rot column. If more than three rot columns are found in a tree, the fourth or fifth rot column may be recorded in a set of columns that has been used previously, provided that at least one row for measurements that is blank in these columns separates the measurements of the two rot columns. Or, if any cross section of the tree bole has more than three cull areas, group the measurements in such a way as to result in recording measurements for three cull areas, one or two of which are actually composed of two separate cull areas.

All measurements recorded on the data sheet should be in feet and tenths and hundredths of feet. Faint vertical lines ruled in the columns would help to guide the placement of digits. To promote accuracy in keypunching, it is essential that digits be placed properly.

Although the heights at which the tree will be cut are already written into the columns headed Height Above Ground, every alternate row has been left blank so that an intermediate cut resulting in 4-foot sections could have measurements recorded. If cuts are taken at irregular heights, record them on the alternate rows and strike out the height figures that are printed on the other lines. At the top of the tree, record total tree height on an alternate line (unless by chance tree height is identical with one of the heights printed on the form), and record 000 under 1 and 2 for both DOB and DIB.

Input Data for Felled Tree (Example 1)

A set of cards with felled-tree data (figs. 4 and 5) ready for a run is listed in figure 7. This example also shows two additional problems with the transition cards needed to terminate a problem and a run.

The format of the tree data in this example is as follows:

	Column
Plot number	1-3
Tree number	4-6
Species	10-12
D.b.h. (1/10 inches)	13-15
Age	16-18
Height of section (1/10 feet)	22-26
D.o.b.	27-29
D.o.b.	30-32
D.i.b.	33-35
D.i.b.	36-38
DBT	39-41
1st Dim. of 1st cull column	42-44
2nd Dim. of 1st cull column	45-47
Shape of 1st cull column	48
As above for 2nd cull column	50-56
As above for 3rd cull column	58-64
F for fork indicator	78

Figure 7.--List of input data cards for felled trees ready for computing. The first two trees represent the data shown in figures 4 and 5.

To ensure that tree measurements are punched into cards accurately for easy processing, special care must be taken in recording dendrometer measurements. Another important reason for being careful in recording data is that a measurement once lost cannot be retaken 6 months later when one is a thousand miles away.

The form we have used (fig. 8)[11] for recording dendrometer measurements in the field has several spaces marked at the top where information pertaining to the entire tree is recorded. These spaces are named and carry numbers corresponding to the data card columns in which the digits recorded therein will be punched. The bottom portion of the field form contains four columns (T, F, S, and G), which are used to record measurements taken on the bole. Each row, across all four columns, contains the measurements taken at a particular height on the tree. Thus, a single row of figures on

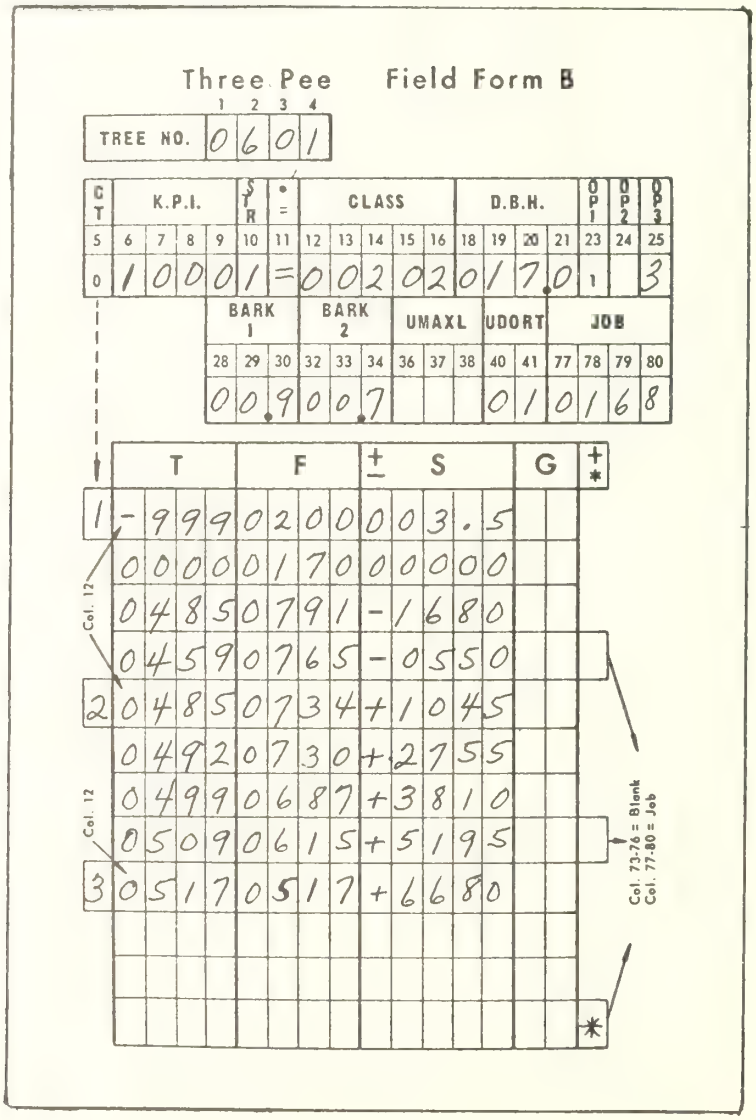

Figure 8. -- Dendrometer measurements for non-forked tree recorded on field form.

[11] Designed by F. A. Johnson, Pacific Northwest Forest and Range Experiment Station, U.S. Forest Service.

the lower portion of the [illegible]
the tree. Column F contains the FGRADS reading, and column S contains the sine of [illegible]
tion reading. Four rows across the columns contain the data to be punched into one
card. Note that the first, fifth, and ninth lines have space for an extra digit on the
left edge of the TGRADS column. In these places put 1, 2, and 3 in consecutive order
to denote the first, second, and third card on which the data will be punched. If the
number of measurements taken on any tree necessitates continuation on another card,
write 4, 5, 6, etc., in corresponding spaces on the second card. The fourth, eighth,
and twelfth lines contain similar extra spaces at the right of the double column
headed G. The characters written in these spaces denote the last measurement for a
particular tree on a given punch card, and signify the kind of measurements for the
same tree that will follow on the next punch card. This will be discussed in detail
later.

Consider once more the data spaces on the top half of the field form. What follows describes the entry of data into them.

Item	Column
TREE NO.	1-4
C1 (Card counter)	
KPI (Value prediction in 3P sampling	6-9
STR (Stratum)	10
CERT (*, =) (Distinguishes probability-sample trees from sure-to-be-measured trees in 3P sampling)	11
CLASS (Species)	12-16
D.b.h. (Inches and tenths. Decimal is implied between columns 20 and 21)	18-21
OP1 . . . OP3 (Not used by NETVSL)	23-25
BARK1 (Inner two bark thickness measurements taken at breast height	28-30
BARK2 Implied decimals between columns 29-30 and 33-34, respectively)	32-34
UMAXL (Not used by NETVSL)	36-38
UDORT (Not used by NETVSL)	40-41
JOB (Use only 3-digit plot number number for NETVSL. Enter zero in column 77)	77-80

The top portion of the field form (fig. 8) can be completed in far less time than it takes to tell about it. Dendrometer measurements are recorded on the lower portion in the columns headed T, F, and ±S. The column headed G may be used to record the grade of the section below the point of observation. The following section on measurements describes the proper recording of data line by line and column by column, following the sequence in which measurements will be taken.

First Measurement

The first measurement to be recorded is stump diameter. The one-digit box added at the left edge of the first line of column T contains 1. This shows, when the data are punched into cards, that the card containing the first four rows of dendrometer measurements is first in the sequence of dendrometer cards for this particular tree.

In the T column, enter -999. This is not a real TGRADS reading, but it signifies that this is the first measurement on the tree and that it is a taped measurement rather than a set of dendrometer readings. In the F column, 0200 is recorded--the stump diameter (o.b.) of the tree, 20.0 inches. The decimal point is understood to be between the third and fourth digit of 0200. It is not written on the field form, but the computer program assumes it to be there when the data are processed. The leading 0 is written in to fill the space. In the ±S column, 003.5 is entered. Although this is the sine elevation column, the number entered here on the first row is not a sine elevation because the first measurement is not a dendrometer measurement. Rather, this entry is the distance in feet up the tree to the next measurement. On this tree it was 3.5 feet from stump height to breast height, where the next measurement was taken. The decimal point in this entry is written by the notekeeper. Leading 0's are also entered as shown in figure 8.

Second Measurement

The next measurement on the tree, which is d.b.h. measured with a tape, is recorded on the second row. For this level, four 0's are entered in the T column. Diameter at breast height, in inches and tenths, is entered on the second row in column F in the same way that stump diameter was entered on the first row. For this tree, d.b.h. was 17.0 inches. In the upper part of this form, 0170 is entered in the d.b.h. space. In the second row of the ±S column, five consecutive 0's are entered for this measurement. This shows that the next measurement on the tree, which follows on the third row, will be taken at the same height as the second measurement.

Third Measurement

The third measurement is d.b.h. again, but measured this time with the dendrometer. Now, on the third row the T column contains, at long last, a true TGRADS reading, namely, 0485, entered as shown. Column F contains a true FGRADS reading, 0791, entered as shown. The ±S column contains the first sine elevation reading, namely, -1680.

Subsequent Measurements

Dendrometer readings for the first level of measurement above breast height are recorded on the fourth row. In this example, sine elevation readings are increasing and continue to increase to the top of the tree. Notice also that all sine elevation readings end in either 0 or 5. This is because it is possible to estimate the instrument reading to this degree of precision, but no closer. Even so, this is more precision than the instrument was intended to give. However, if the instrument location is changed,[12] the continuous increase in sine elevation may be disrupted. As figure 8 demonstrates, the FGRADS readings usually decrease as tree height increases. Occasionally, FGRADS may increase slightly, but usually they decrease. After each set of instrument readings is taken, the trend of FGRADS should be checked; if an increase is noted, measurements should be checked before the instrument is moved. A short section of a tree trunk may show negative taper, but this is fairly uncommon. The third level of measurements above breast height is recorded on row 5 of this field form. A 2 is recorded in the box at the left of the T column to show that this row records the first set of readings that will be punched into the second data card for this tree.

Measurements are taken at irregular intervals up the stem separating portions of uniform taper and grade. Readings taken at the top of the tree are recorded on line 9 of the field form. The TGRAD and FGRAD readings at the top of the tree are identical, indicating a zero diameter. The last box on the right of the G column at the bottom of the field form contains an asterisk (*), which shows that the third punched card will be the last card containing data for this tree.

[12] One move to a different instrument location up or down hill is permitted.

Continuation on a Second Sheet

If enough measurements are taken on a tree that they cannot be recorded on a second sheet, fill the spaces at the end of the second sheet from the first card. Write "continued" at the top of the second sheet (and the third, if necessary). On the first sheet write "1 of 2" or "1 of 3" in the upper right-hand corner. On the second (or third) write "2 of 2" or "3 of 3," etc., in the upper right-hand corner (fig. 9).

Forked Trees

Figure 9 shows how data for forked trees are recorded. After the stump and d.b.h. measurements are recorded, instrument readings are recorded up to the last measurement below the fork, corresponding to measurement 4. The readings taken at such a point were recorded on the fourth row of the first sheet. The sine elevation reading at this level is -1000, and a plus sign (+) is recorded in the extra box on the right edge of column G. This keys the computer program to compute the volume of the next section of tree trunk separately and to add it to the volume that has already been accumulated.

Measurements for the first fork follow, starting on the fifth row. Note that the sine elevation recorded for the bottom of the fork is about the same as that recorded for the top of the first trunk section. Measurements are then taken up the stem of the fork and recorded as shown. At the top of the first fork, TGRADS and FGRADS readings are equal (line 11 of card 1). No dendrometer readings are recorded on the twelfth line.

The measurements for the second fork are punched into a different set of data cards. In the deck of punched cards for a tree, it is essential that measurements for the portion of the trunk below a fork and for the forked portions not be punched into the same card. For this reason the twelfth line on the first card is left blank except for the slash (/) in the extra box at the right of column G. On the first line of the lower portion of the sheet for this tree (which will be the first set of measurements on the fourth punched card), are entered the dendrometer readings for the bottom of the second fork. Dendrometer readings are then recorded for successive levels of measurement up the stem of the fork until the top is reached. The first box at the right of column G following the last entry of data (which happens to be on the same line on this card) then contains an asterisk (*) to signify the end of data for that tree.

Change in Instrument Location

The dendrometer may be moved from one observation level to another without special recording procedures *only if* the new location is on the same horizontal plane as the previous location.

One move to a different horizontal plane is permitted. The way in which data are recorded after change to a new elevation is shown in figure 10. Measurements are taken and recorded in the usual fashion until it is desirable to move the instrument to a new location. Readings taken at this new level are recorded on line 6 of the sample form (fig. 10).

Data for forked trees require special precaution when the instrument is moved because the plus character is used to indicate both (1) the point at which a fork leaves the bole and (2) the relocation of the instrument. To overcome this ambiguity, the convention has been adopted that only the first plus recorded for a forked tree can represent a relocation. All subsequent plus characters are interpreted as fork locations. A + sign is then placed as shown on line 8. After the instrument is set up at the new location, a measurement is taken at the same height on the tree as the last

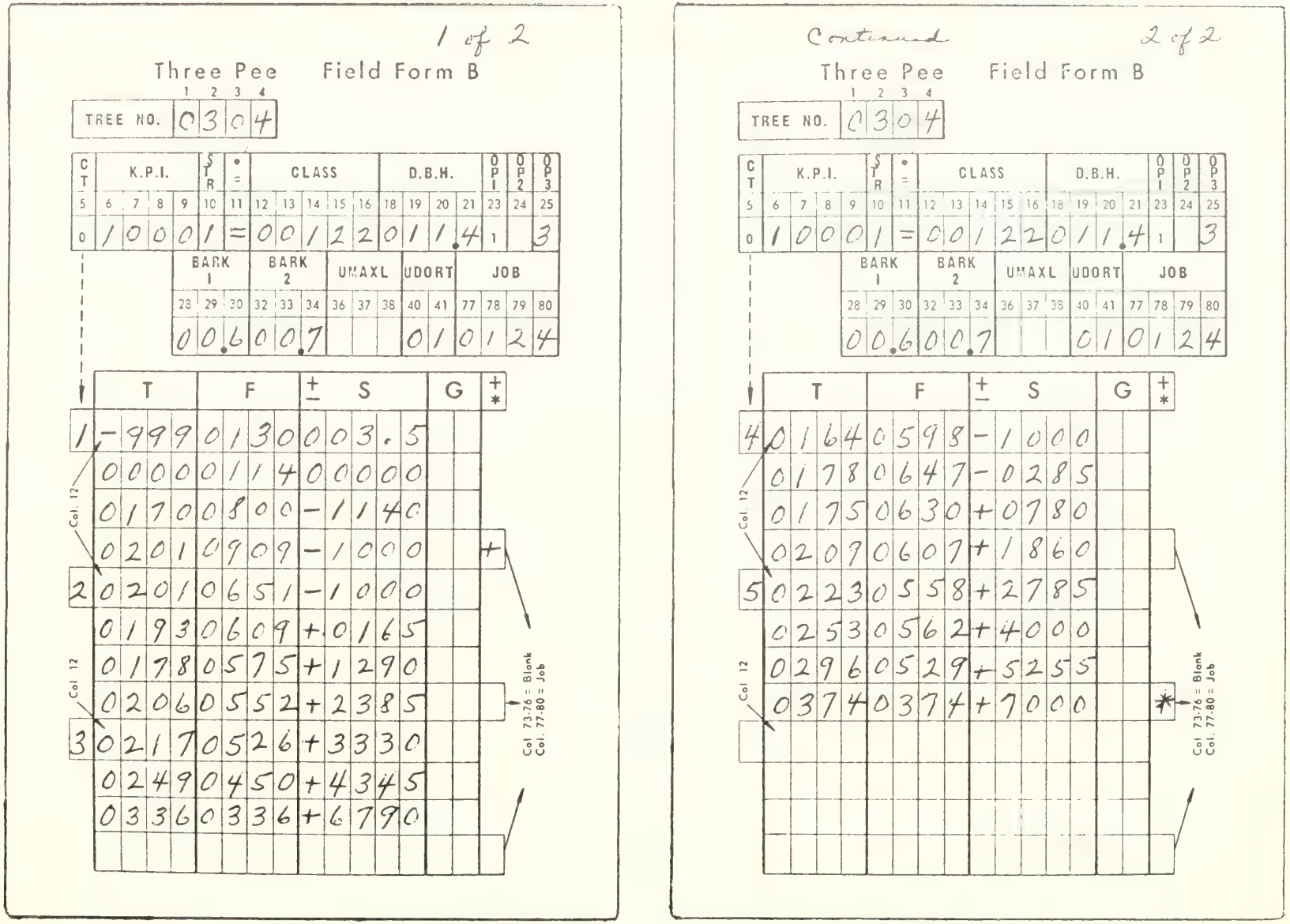

Figure 9.--Record of dendrometer data for a forked tree.

measurement taken at the previous location. Therefore, the data recorded in (fig. 10) were taken at the same height as those recorded at the previous location. Measurements are then taken and recorded up to the top of the tree in the normal manner.

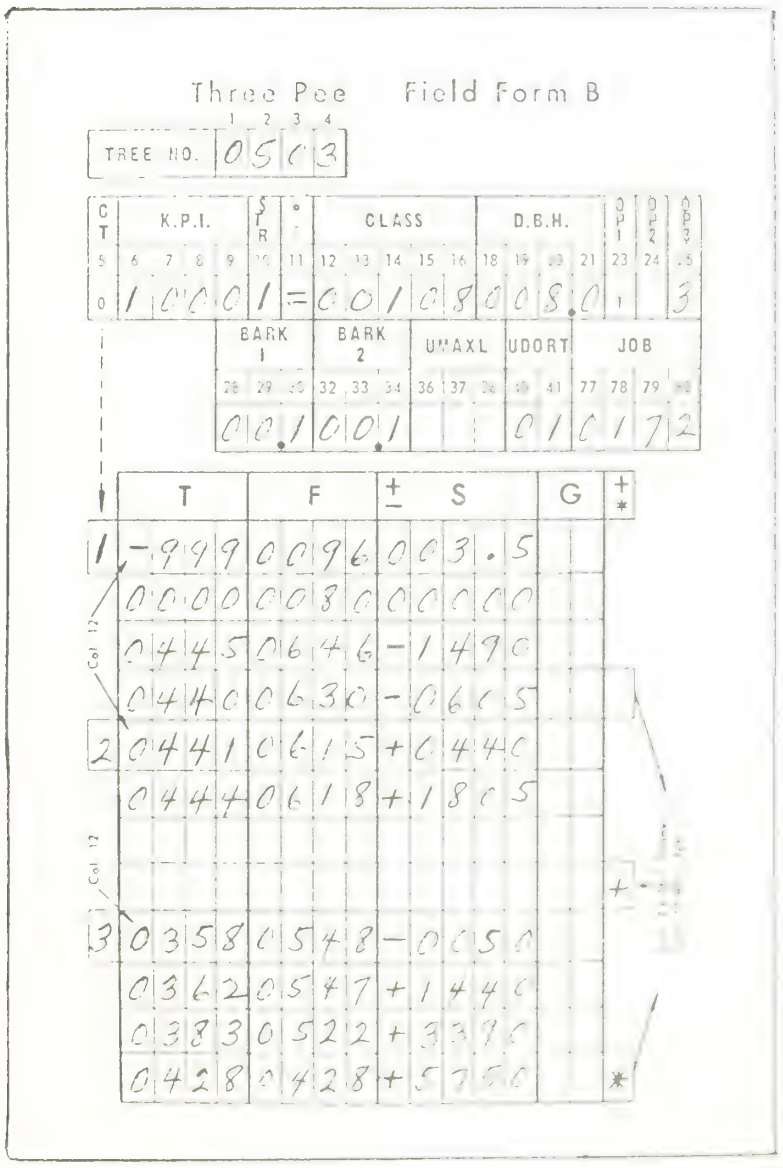

Figure 10.--Recording dendrometer data when instrument location is changed.

APPENDIX B

ERROR MESSAGES AND DIAGNOSTICS

The main program in NETVS1 calls many subprograms to perform the various parts of the calculations. After the calls to most of the subprograms, the main program tests the status of the variable: IERROR. If IERROR is nonzero, this error message is printed in which xxxxx, yyyyy, and zzzzz are replaced by the values of IERROR, JERROR and KERROR, respectively:

ERROR xxxxx HAS OCCURRED IN SECTION yyyyy. ERROR COUNT = zzzzz.

The value of KERROR is incremented by one *each* time an error condition is encountered, and the tree is omitted from further processing.

The values of IERROR and their associated diagnostics are grouped by the subprograms in which they arise in the following list.

Subprogram	IERROR	Interpretation
DIALEN	401	Number of sections is greater than the 40 storage locations provided. If this is true, the program dimensions must be increased. Otherwise, look for such situations as duplicated tree numbers in successive trees, or missing asterisks on dendrometer cards.
	402	Number of forks is greater than the eight storage locations provided. If this is true, the program dimensions must be increased, or the tree pruned.
	403	Number of forks as indicated by the occurrence of fork codes does not match the number of tops indicated by zero diameters. Check for missing fork codes or extraneous zero diameters.
	404	Negative diameter found. Check data for cause.

Each of the above errors will cause DEBUG output to be printed.

BOARDF	801	See DIALEN 401 above.
	802	Indexes are in error in calculating the positions of saw-log tops. If there are no previous errors for this tree, obtain DEBUG output and consult with the senior author.
CUAREA	1101	An error has occurred in matching the cull codes of the data with the cull code keys stored in BLOCK DATA. This matching is accomplished in CULVOL. Check that NCODE has not been initialized to a value greater than 10 in BLOCK DATA.

READIN	1201	The plot number on the section being processed does not agree with the plot number on the preceding PLOT OPTION CARD. Check data sequencing.
	1202	See DIALEN 401 above.
	1204	A card sequence error has been detected among the dendrometer cards. Check data sequence.
FORMF	1301	Form factor of nonforked tree is suspiciously large.

In addition to the above errors, which will cause the offending tree to be skipped, one message that may be printed in DIALEN may indicate erroneous data. DIALEN checks that the length of each section is greater than 0.0001 foot. If not, the message:

LENGTH OF SECTION I(I) y CHANGED TO 0.0001

is printed with the index of the section and its prior length inserted in place of I and y, respectively. With dendrometry data, small negative lengths may result from small errors of measurement of closely spaced sections. In this case, if FLN(I) is reasonably close to zero, the volume calculations should not be seriously affected. Otherwise, the data sequencing and recording should be checked for errors.

Stage, Albert R., Richard C. Dodge, and James E. Brickell.
1968. NETVST: A computer program for calculation of tree volumes with interior defect. Intermountain Forest and Range Exp. Sta., Ogden, Utah, 84401. 30 pp., illus. (U.S. Forest Serv. Res. Pap. INT-51)

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CONE SEROTINY OF LODGEPOLE PINE NEAR ISLAND PARK, IDAHO

JAMES E. LOTAN

RESEARCH PAPER INT-52, 1968
Intermountain Forest & Range
Experiment Station
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U.S. Forest Service
Research Paper INT-52
1968

CONE SEROTINY OF LODGEPOLE PINE NEAR ISLAND PARK, IDAHO

James E. Lotan

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

INTRODUCTION

The serotinous cone fruiting habit is an important factor in the silviculture of lodgepole pine (*Pinus contorta* Dougl.) in the northern Rocky Mountain and Intermountain regions. The usual practice of block clearcutting depends upon an adequate supply of stored seed in serotinous cones (Bates, Hilton, and Krueger 1929; Boe 1956; Tackle 1961, rev.; 1964). Lodgepole pine does not normally disperse sufficient seed for adequately reproducing a stand beyond about 3 chains from the timber edge (Boe 1956; Tackle 1964). The several years' seed supply stored in serotinous cones is the source of seed for regenerating the clearcut block beyond this distance. Natural regeneration is usually superabundant. However, areas exist where regeneration has been difficult to obtain, particularly in southeastern Idaho.

Most Rocky Mountain stands have been considered as bearing an abundance of serotinous cones, but recent evidence has shown that significant local variation exists (Lotan 1967). Individual trees in the same stand vary in fruiting habits, most trees distinctively bearing either open or closed cones (Clements 1910; Mason 1915); and to date no one has clearly demonstrated causal factors related to the habit. (In this paper, the term "closed cone" is equivalent to "serotinous cone.")

To learn more about the degree of cone serotiny in lodgepole pine and the number of closed cones per acre, we sampled stands on two physiographic areas located just west of the Continental Divide near Island Park, Idaho, on the Targhee National Forest. The survey was started in 1961 and completed in 1964 using a previously developed sampling technique (Lotan 1963). The areas had been designated as difficult to reforest, and other regeneration studies (including seedling survival studies) were centered there (Lotan 1964a).

METHODS

Sampling was stratified by two elevational levels (fig. 1) divided by a plateau front at about 7,000 feet elevation: (1) Island Park Flat with an average 6,500-foot elevation and (2) Moose Creek Plateau with an average 7,700-foot elevation. A total area of about 60,000 acres (nearly equally divided between the two elevational strata) was sampled within the boundary of the Moose Creek Plateau timber sale of 1960. Some stand characteristics from the two strata are compared in table 1.

SAMPLING TECHNIQUE

Fifty-nine systematically located 1/50-acre plots were established in alternate square miles, and a total of 229 trees sampled. Within each plot all trees 5.6 inches d.b.h. and larger were felled, and closed cones were counted on 25 outer-1-foot branch segments in the upper portion of the crown of each tree. The tree was sampled from the top downward until the 25 samples were taken. All closed cones were counted on 59 trees to obtain a regression formula for estimating total closed cones on the remaining trees. Part of these total-count trees were used in a previously reported formula (Lotan 1967). From these data the following regression formula was computed:

$$\hat{Y} = 253X - 215$$

where $\hat{Y}$ = total serotinous cones per tree, and X = mean serotinous cones per sampled branch segment. The correlation coefficient is 0.814, and the standard error of estimate is 84 cones. The half-confidence interval for the population mean is 114 cones per tree at the 5-percent level of probability.

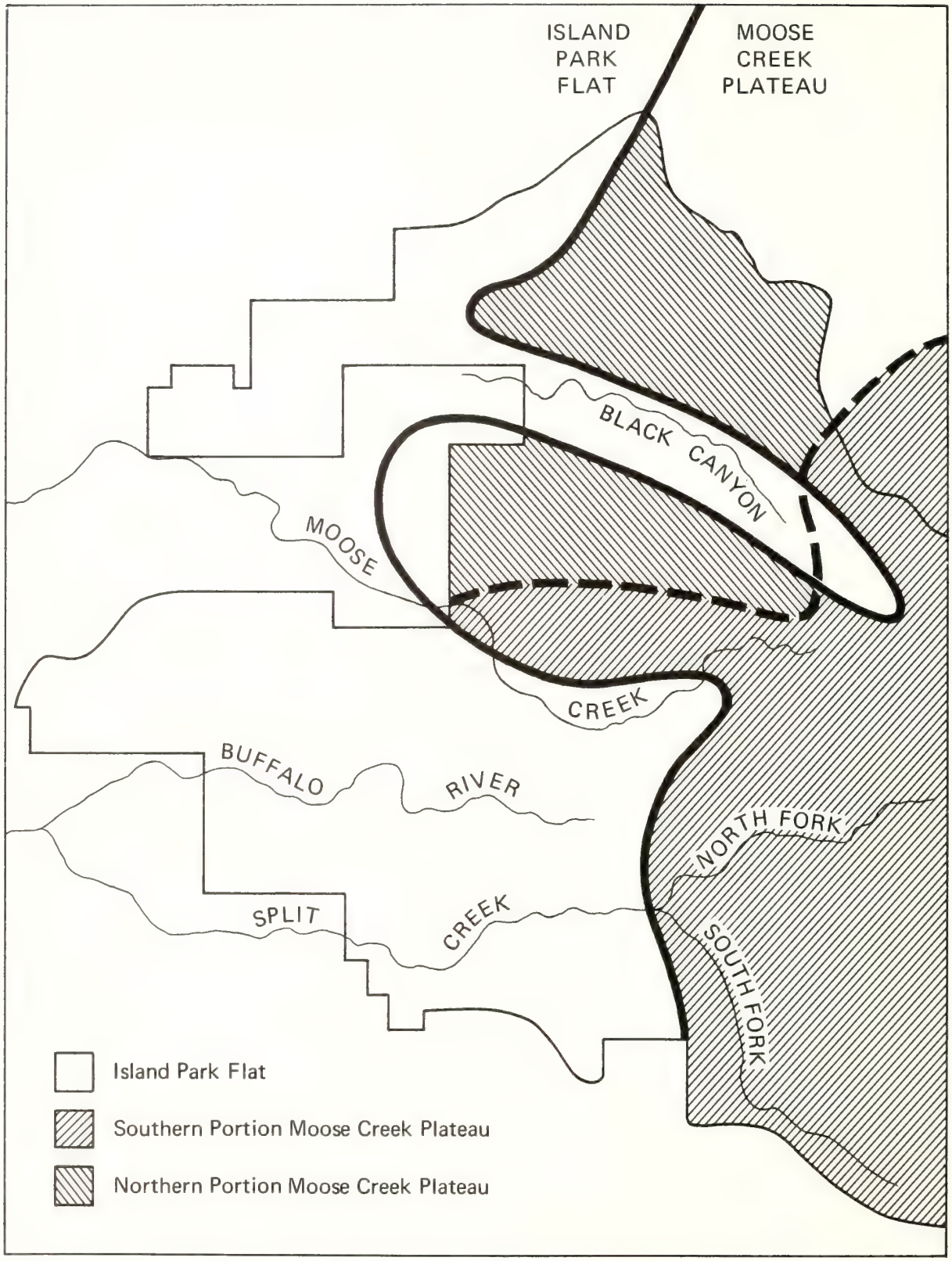

Figure 1.–Location of study area, Island Park Ranger District, Targhee National Forest, Idaho, 1964.

Current and open cones were counted on the 25 samples from each tree to determine the percentage of closed cones per tree and the percentage of trees bearing closed cones in the stands. This gave a tree-by-tree comparison of the closed-cone habit independent of variation in cone production of individual trees.

Data were collected on plot and tree factors that we thought might be related to the percentage of serotinous cones on a tree: elevation of the plot; and a numerical rating of dwarfmistletoe, d.b.h., total height, percent live crown, crown class, vigor class, and age for each tree.

Table 1.– *Characteristics of stands in serotinous cone survey, Targhee National Forest, 1964*

Study area	Average age	Average d.b.h.	Average total height
	Years	*Inches*	*Feet*
Island Park Flat	117 ± 8[1]	10.0 ± ½	66 ± 2
Moose Creek Plateau	191 ± 12	12.5 ± ½	61 ± 2

[1] *Standard error of the mean at the 95-percent level of probability.*

RESULTS AND DISCUSSION

The results on the Targhee National Forest were similar to those obtained on the Gallatin National Forest (Lotan 1967) in that adjacent areas have produced varying degrees of cone serotiny. The trees on Island Park Flat produced more than three times as many serotinous cones per acre as those on the upper level (table 2). These stands had more trees per acre, a greater average number of closed cones per tree (table 2), and a greater percentage of trees bearing predominantly serotinous cones (table 3) than stands on the Moose Creek Plateau.

Also, as previously reported (Lotan 1967), the closed-cone fruiting habit of individual trees on these areas was usually quite pronounced. Only about 20 percent of the trees were classified "intermediate" (table 3) in fruiting habit on both areas–slightly more than the previously reported 10-14 percent. Trees were classified as *serotinous* if they bore 90 percent or more closed cones and *open* if they bore 10 percent or less closed cones. Of the trees growing on Island Park Flat, 48 percent were serotinous; of those on Moose Creek Plateau, 23 percent were serotinous.

Although data collected on the Moose Creek Plateau were not formally substratified, a sharp break was observed in the number of cones per acre north and south of a line indicated in figure 1. North of this arbitrary line (no logical basis was found to stratify these data other than the difference in results) plots averaged 105,000 cones per acre, and more than half of the plots had over 100,000 cones per acre. South of this line, average number of cones per acre was only 15,000, and over half of the plots had no cones. The percentage of "serotinous" trees was not too greatly different on these two substrata–19 percent on the southern portion and 26 percent on the northern portion.

It is difficult to explain the differences in fruiting habit obtained in this study. A multiple regression of recorded plot and tree factors explained less than 10 percent of the variation in percentage of serotinous cones per tree. The two most obvious statistical contributors are elevation and age of the stands. However, superimposed upon this is a difference in stand history. Most of the Island Park Flat has been "tie-

Table 2.--*Estimated average serotinous cones per acre in stands near Island Park, Idaho, 1964*

Study area	Average trees per plot	Average serotinous cones per tree	Average serotinous cones per acre	Average sound seed per cone[1]	Average sound seed per acre
			Thousand		*Million*
Island Park Flat	4.4	772	173	10.7 ± 3.1	1.8
Moose Creek Plateau	3.5	295	53	15.7 ± 3.2	0.8
North portion	4.2	500	105	16.2 ± 5.4	1.7
South portion	3.1	94	15	15.1 ± 3.7	0.2

[1]*Standard error of the mean at the 95-percent level of probability.*

Table 3.--*Variation of serotinous cone habit in stands near Island Park, Idaho, 1964*

Study area	Trees bearing predominantly serotinous cones[1]	Trees intermediate in cone habit[2]	Trees bearing predominantly open cones[3]
		Percent	
Island Park Flat	48	19	33
Moose Creek Plateau	23	20	57

[1]*Trees bearing 90 percent or more serotinous cones.*
[2]*Trees with more than 10 but less than 90 percent serotinous cones.*
[3]*Trees bearing 10 percent or less serotinous cones..*

hacked," that is, selected larger trees (11 to 16 inches d.b.h.) were removed for railroad ties about 1935. Most of the stands on the Moose Creek Plateau are extremely overmature, with individual trees over 400 years old. A linear regression with plot elevation and tree age as independent variables explained only 5 percent of the variation. On the Gallatin National Forest (Lotan 1967) a strong genetic component was suggested because the highest percentage of serotinous-coned trees occurred in an even-aged stand originating from fire–these trees no doubt originated from closed cones in the previous stand. In that study the high percentage of open-coned trees was found in stands that, for the most part, originated from open-coned trees.

Crossley studied fruiting habit of lodgepole pine in Canada (Crossley 1956) and suggested a possible age relationship to closed-cone habit, with very young stands (17 years old) bearing open cones and 55- to 250-year-old stands bearing closed cones. In the present study the age spread was too limited to detect this relationship.

Silviculturally, the data show that there should be sufficient seed stored in closed cones to regenerate the stands by block clearcutting if slash is handled properly (Boe 1956; Lotan 1964b; Tackle 1964). Slash must be exposed to radiant energy near the surface of the ground to melt the resin bond holding the cone scales and must be dozer-piled before germination occurs. Timing is of the essence.

The amounts of seed stored in closed cones as reported in this study give approximate estimates of the biotic potential for seedling establishment beginning with sound seed. Other studies such as that reported by Lotan (1964a) provide guides to the probabilities for germination and survival of available seed. However, the results as reported by Lotan were values for an above-average year with respect to moisture conditions.

The estimated sound seed values on the Moose Creek Plateau may be marginal. If we assumed a goal of 1,000 established 1-year-old seedlings per acre and a probability of 0.02 (seed-to-seedling ratio of 50:1) for seedling survival after 1 year, we would then need 50,000 sound seed per acre to produce our goal of 1,000. Our unknown probability in this situation is the proportion of the 800,000 sound seed per acre that will be released from cones and fall upon the soil. This gives us 16 times the number of seed required upon the seedbed to allow for this unknown probability. This amount will probably be adequate for good years but may not be so for abnormally dry years. We need more information on probabilities of success.

This study accomplishes little toward elucidating factors of cone serotiny except to point out problems involved in studying the matter and some implications of local variation. We are left with many questions. What is the relation between the serotinous cone habit and fire? Is regeneration by fire highly selective for the closed-cone habit as I hinted in discussion of the Gallatin National Forest data (Lotan 1967)? What is the relation of serotinous cone habit to other destructive agents such as the mountain pine beetle and dwarfmistletoe? What are the effects of management in selecting for or against the closed-cone habit? Because of the importance of the cone habit in the silviculture of lodgepole pine (whether for timber, watershed, esthetics, or whatever), further research is needed into this interesting phenomenon.

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Stands of *Pinus contorta* Dougl. on adjacent physiographic areas in southeastern Idaho vary in the serotinous cone fruiting habit. On the Island Park Flat (average elevation 6,500 feet) 48 percent of the trees were classified as predominantly serotinous cone trees (bearing 90 percent or more serotinous cones). On the nearby Moose Creek Plateau (average elevation 7,700 feet) only 23 percent of the trees were classified as serotinous cone trees. The Island Park Flat produced 173,000 serotinous cones per acre, whereas the Moose Creek Plateau produced only 53,000 such cones per acre. Cone habit showed no relation to common plant and tree parameters measured.

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EFFECTS OF SEEDBED TREATMENT ON GRASS ESTABLISHMENT ON LOGGING ROADBEDS IN CENTRAL IDAHO

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EFFECTS OF SEEDBED TREATMENT ON GRASS ESTABLISHMENT ON LOGGING ROADBEDS IN CENTRAL IDAHO

by

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INTRODUCTION

Soils derived from the granite of the Idaho Batholith of central Idaho erode rapidly when disturbed or bared by man's activities. Thus, logging roads needed to develop the timber resource necessarily expose a large area of unstable soil to damage by erosion. As a remedial practice, the bared areas are sown with perennial grasses that develop deep, fibrous root systems capable of binding and holding the soil, and that also provide litter cover and protect the soil from raindrop splash.

The seeding is usually done when logging roads are "put-to-bed" following timber harvest operations. Either motorized or hand seeders are used to broadcast seed. Usually no attempt is made to cover the seed or to precondition the hard-packed roadbed before seeding. The accepted practice in this area is to broadcast a mixture of seeds late in the fall. In the ponderosa pine areas east of the Cascades in Oregon and Washington, fall seeding is also the practice, according to Gjertson (4). The seeds lie dormant over winter and germinate as soon as snow disappears in the late winter or early spring. Experience has shown that spring seeding generally results in failure because the poorly developed seedling root systems cannot survive the hot, dry summers.

Field results from broadcasting seed have varied because of the diverse site conditions associated with roadbeds. Poor stands of perennial grasses have been as common as good stands. Consequently a more reliable method of establishing a dense grass cover on roadbeds is needed.

This paper presents the findings of a reseeding study designed to determine (a) whether scarifying a hard-packed roadbed, either before or after broadcasting seed, leads to establishment of a better stand of grass than one grown on an untreated roadbed, and (b) whether a wood-chip mulch, with or without fertilizer, further encourages the growth of grass. A secondary objective was an evaluation of the survival of five well-known perennial grass species growing on an extremely harsh site--the bare surface of a logging road.

DESCRIPTION OF THE STUDY AREA

The experimental area is 20 miles northeast of Idaho City on the Little Owl Creek drainage of the Boise National Forest. The elevation ranges from 5,000 to 6,000 feet and land slopes are moderately steep, averaging 46 percent (5). At this altitude ponderosa pine and Douglas-fir grow in mixed stands. The soil, a coarse-textured loamy sand typical of the Idaho Batholith, has a weak profile development, low humus content, and low water-holding capacity, and is highly erodible.

In the 3 years of study, annual precipitation as measured in gages within the study area, averaged 37 inches; of this amount 10.0 inches was received in the period April 1 through September 30, which includes the growing season. Within the period, April and May rains accounted for 7.8 inches; the remaining 2.2 inches fell during the 4-month dry period, June 1 through September 30. Compared with long-term U.S. Weather Bureau records for the closest stations, growing-season rainfall on the Little Owl area was slightly above normal for the three growing seasons following seeding.

ESTABLISHMENT OF THE STUDY

Two logging roads, each 1 mile in length, were selected for the study. One road was on generally south-facing slopes; the other on generally north-facing slopes. Hauling over the roads had ceased by October 1955, and earthen cross drains had been constructed at prescribed intervals ranging from 50 to 100 feet; the interval between these cross drains was designated a study plot. There were 64 plots per road, a total of 128.

The scarification treatments were

a. No roadbed preparation before or after broadcast seeding--(control).

b. Scarifying to a depth of 3 inches with a spike-tooth harrow, after seeding.

c. Scarifying to a depth of 12 inches with a six-tooth ripper mounted under a road patrol, after seeding.

d. Deep scarifying (12 inches) as in (c) above, followed by seeding.

These treatments were applied on the ground in groups of four contiguous plots of each treatment to minimize vehicular travel back and forth on roads.[1] Despite these precautions, unavoidable compaction occurred on many plots during the 3-week establishment period in October-November 1955. The scarification treatments (by blocks of four plots) were randomized and were replicated eight times.

The grass seed mixture included five perennials and a cereal grain (winter rye, Secale cereale) to provide temporary litter cover during the critical early years of perennial grass establishment. The perennials were two long-lived sod formers, Manchar smooth bromegrass (Bromus inermis) and intermediate wheatgrass (Agropyron intermedium); and three bunch formers, crested wheatgrass (A. desertorum), timothy (Phleum pratense), and bulbous bluegrass (Poa bulbosa). Although a shallow-rooted grass, bulbous bluegrass had adapted well to dry sites in the Boise National Forest. The rate of seeding for all species combined was 36 pounds per acre, as listed below:

Species	Rate/acre (lbs.)
Winter rye	20
Bulbous bluegrass	2
Standard crested wheatgrass	3
Intermediate wheatgrass	5
Manchar smooth bromegrass	5
Timothy	1

Superimposed upon the scarification treatments after seeding were three additional treatments: (a) fertilizer (equivalent to 40 pounds of nitrogen plus 40 pounds of phosphorus per acre) broadcast with hand spreaders; (b) wood chips (a layer about 1 inch thick) produced by feeding green slash into a tractor-mounted chipper, and spread over the plot manually with pitchforks; (c) fertilizer and wood chips in combination. On the fourth plot, only the scarification treatment was applied. The additional treatments were applied randomly to each group of plots.

[1] The authors acknowledge the excellent cooperation from the Ranger's staff and slash disposal crew of the Lowman District, Boise National Forest.

DATA COLLECTION

Field data were collected July 1-17, 1957, midway in the second growing season. At that time four of the treatment replications--64 plots--were sampled (two replications on each aspect road). One year later, July 1-17, 1958, all of the 128 plots were sampled, although 2 weeks before this sampling began, 21 plots on the south aspect road had been grazed by a band of sheep in trespass.

The density of grass seedlings (live plants per square foot) and the percent of ground cover were used to judge effectiveness of treatment. Sampling in each plot was done on four permanent 72-inch transects staked randomly crosswise to the axis of the roadbed--two in the inboard half and two in the outboard half. A previous survey found that the roadbeds averaged 16.5 feet in width (5). The notched side of a 4- by 72-inch sampling frame was anchored to the transect. Live plants within the frame were identified by species and counted, after which the notched side of the frame was used as a point sampler by insertion of a needlepoint gage at each notch successively. Percent ground cover was estimated from the number of basal hits on live vegetation and plant litter.

When plots were selected for treatment, none was eliminated to reduce experimental error caused by variations in soil, topography, aspect, and roadbed compaction. It was deemed impractical to do this with roads built on irregular terrain. Accordingly, site properties not common to every plot and hence not measured contributed to experimental error. However, site properties common to every plot were indexed empirically if they were thought to be related to seedling emergence and establishment, independent of treatment effects. For example, the percentage of each roadbed plot shaded at noon by surrounding trees and topography was estimated, and later used in an analysis of covariance.

ANALYSES

The data on individual species, on treatment effects, and on certain site properties were examined statistically by analyses of variance and covariance (8).

Some sources of variation that either could not be measured or were not deserve some discussion:

1. Some seed broadcast in the fall were lost through extraneous causes before germination in late winter. Had losses been uniform from plot to plot, the experimental consequences would not have been as serious. However, during the seeding operation small mammals were observed gathering and storing seed taken from some road surfaces but not from others. Obviously, such feeding would leave a nonuniform distribution of seed in the roadbed plots. Therefore, the sparseness of plants in some transects may very well be related to an initial lack of seed and not to differences in treatment and site.

Furthermore, in the time between seeding and germination, two major periods of overland flow occurred when seed may have been washed away completely or redistributed within the plot. The first such period was during the heavy rainstorms of December 19-24, 1955. The second was the normal snowmelt runoff in late March 1956.

2. Such soil properties as compaction, texture, and fertility, had they been defined directly rather than indexed empirically, might have explained more site variation between plots. An intensive study of soil properties should be given consideration in any new reseeding trials.

3. It is problematical whether within-plot variation would have been better defined by more intensive sampling. The decision to use four transects per plot was made primarily to provide a suitable workload for sampling a large number of replications.

RESULTS OF TREATMENTS

Number of plants of all species ranged from 1 to 33 per square foot for the 2 years studied. In 1957 the average density for all treatments was 9.4 plants per square foot; the next year the count was 10.7 plants per square foot if the 21 grazed plots are excluded, or 8.5 plants if the plots are included. The difference in count between years was not significant. The high count observed in the third growing season indicates that the reseeding trial as a whole was successful in establishing an adequate stand of grass under the current climatic conditions. The reseeding study was conducted during a wet climatic period when growing-season moisture was probably quite favorable for grass establishment, regardless of treatment. Thus, the conclusions from this experiment might be different in years of drought.

This performance fell below that reported by Bethlahmy (1) for the Cascade Range of Oregon. There, on logging roads, where precipitation measures 110 inches per year, an average count of 31 plants per square foot was observed. In northeastern Washington, from adaptation tests of 18 forage species broadcast seeded, Evanko (3) found that counts ranged from 0.2 to 22 plants per square foot. His tests were not carried out on logging roads, however, but in ashes of a freshly burned lodgepole pine stand on a shallow, well-drained soil derived from granite.

Table 1 gives the average number of plants per square foot and percent of ground cover for 1957 and 1958 data by scarification treatment, with and without wood-chip mulch. This table shows, for example, the generally higher number of plants on northeast aspect plots and on unmulched plots; and the slight superiority of the scarify-and-seed treatment over the other three. Two plots representative of low and high average number of plants per square foot are shown in figures 1 and 2.

Table 1. Average plant density and percent general cover according to treatment and aspect, Little Owl logging road

Scarification and other treatments[1]	Southwest aspect				Northeast aspect			
	Plants per sq.ft.		Percent ground cover		Plants per sq.ft.		Percent ground cover	
	1957	1958	1957	1958	1957	1958	1957	1958
Seed (control):								
Without wood-chip mulch	10.3	6.9	7.0	7.3	11.1	8.6	13.0	5.8
With mulch	6.7	6.9	5.9	5.2	12.8	12.5	7.1	5.4
Seed, harrow:								
Without mulch	10.7	10.1	7.6	6.1	11.6	9.4	8.5	6.2
With mulch	5.1	5.6	1.5	5.2	7.1	6.8	4.1	2.4
Seed, scarify:								
Without mulch	6.5	6.2	5.2	6.2	11.0	9.0	19.8	5.5
With mulch	5.9	7.2	5.5	5.7	7.4	8.1	3.8	3.5
Scarify, seed:								
Without mulch	10.9	13.5	8.0	7.5	14.4	11.3	16.9	4.6
With mulch	8.0	8.0	2.8	5.9	10.4	8.6	4.4	3.3

[1]Figures for treatments combine results for the treatment alone and the treatment plus fertilizer.

Figure 1.--Effect of wheel compaction on roadbed plot 27. This plot has an average of six plants per square foot.

Figure 2.--Roadbed plot 76, north facing and nearly level, with an excellent stand of grass averaging 24 plants per square foot.

SCARIFICATION

Comparison tests between scarification treatments and controls revealed the results given in table 2. As indicated, the deep scarification treatments varied significantly from the control both in 1957 and 1958. Seeding of grass prior to deep scarification proved less effective than seeding alone, probably because the ripping action covered some seed too deeply. On the other hand, seeding of grass immediately following deep scarification proved to be a slightly better method of increasing plant density. Postseeding may have had two advantages: (a) it allowed loosened soil material to slough and cover seed, and (b) it permitted surface water and seedling roots to penetrate easier.

MULCH AND FERTILIZER

Results of additional treatments are shown in table 3. Mulching with wood chips had a depressing effect on plant density. When fertilizer was added with the wood chips, the decrease in plant count was less than with wood chips alone, although the difference was not significant. The use of fertilizer alone appeared to be related to an improvement in plant density although, again the difference was not significant in either year of study. Klomp (7), in reseeding scablands in Oregon and Washington, included treatments using 1/2- and 1-inch layers of wood chips, disked in and not disked, with nitrogen fertilizer and without. He found that chips plus nitrogen fertilizer (300 lbs. N per acre per inch of chips) yielded best results. This is contrary to our findings, where plots treated with a mixture of wood chips and fertilizer yielded fewer plants per square foot (although not significantly so) than untreated plots. This discrepancy may exist because in our study a much smaller amount of nitrogen fertilizer was applied per acre. It is also entirely possible that available nutrients from the small amount of fertilizer used had leached out of the soil by the second growing season, resulting in a lack of significant difference in growth between fertilized and control plots.

Table 2. Effects of scarification treatments

Treatment	Plants per sq.ft.		Percent ground cover	
	1957	1958	1957	1958
Broadcast seed (control)	9.4	10.7	8.2	12.5
Seed, harrow	9.3	12.2	5.4	13.6
Seed, deep scarify	5.4**	7.1**	8.6	11.9
Deep scarify, seed	13.4*	12.5*	8.0	11.2

* Comparison with control significant at 7-percent level.
** Comparison with control significant at 5-percent level.

Table 3. Effects of wood-chip mulch and fertilizer

Treatment	Plants per sq.ft.		Percent ground cover	
	1957	1958	1957	1958
Control	9.4	10.7	11.5	16.3
Wood-chip mulch	5.8*	12.2	3.0*	9.6*
Fertilizer	10.6	8.9	10.0	12.1
Mulch and fertilizer	7.4	9.4	5.6*	11.6

*Comparison with control significant at 1-percent level.

EFFECT OF SITE VARIABLES

Several site properties affected plant density in the 2 years of measurement. Plant density was related positively to aspect. The density of plants per square foot increased as the roadbed aspect changed from south to north.

The amount of shade cast by surrounding trees and topography was related beneficially to plant density, but not significantly so.

Roadbed compaction caused by posttreatment vehicular trips back and forth over the roadbed had latent adverse effect on plant density (see fig. 1).

SPECIES PERFORMANCE

Results in terms of seedling establishment for the six species are shown in table 4. Manchar smooth bromegrass and the two wheatgrasses--intermediate and standard crested--produced the greatest number of plants per square foot, almost 71 percent of the total plant count. Their establishment percentages, based upon number of viable seeds broadcast per square foot, were also the highest, 16 to 22 percent, indicating that of the five perennials tested, these three grasses appeared to be best adapted to the growing conditions of the study area. Interestingly, in 1957 smooth bromegrass and winter rye were more abundant on the cool, northeast aspects than on the southwest aspect. The southwest aspect was superior for bulbous bluegrass. By 1958, winter rye had practically disappeared from the roadbeds.

Other adaptability studies conducted in the ponderosa pine zone of the Intermountain and Rocky Mountain regions show Manchar smooth bromegrass and the two wheatgrasses as being well suited. Evanko (2), working in a large ponderosa pine opening in northeastern Washington, rated the wheatgrasses in a superior group and Manchar smooth bromegrass in the next-best group. He found timothy unsatisfactory in all respects, but rated orchardgrass as good as the wheatgrasses. Johnson and Hull (6) reported that intermediate and crested wheatgrass, smooth and meadow bromegrass, Russian wildrye, and big bluegrass out of 82 species tested appeared to be the most vigorous and generally adapted to central Colorado.

Table 4. Seedling establishment data for six grass species

Species	Maximum possible germination[1]	Mean seedling establishment		Seedling establishment			
				1957		1958	
		1957	1958	Southwest	Northeast	Southwest	Northeast
	--Seeds/sq.ft.--	--Plants/sq.ft.--		----------Percent----------			
Wheatgrasses Crested) Intermediate)	[2]23.0	3.7	3.9	15.8	16.0	17.8	16.3
Manchar smooth bromegrass	14.8	2.9	2.3	15.8*	22.0	16.8	14.8
Timothy	24.0	1.7	1.3	8.4	6.3	5.0	5.4
Bulbous bluegrass	18.6	0.6	0.8	3.9*	1.8	5.8	3.4
Winter rye	7.9	0.5	0.2	4.7*	6.7	2.0	1.8
Total[3]		9.4	[4]8.5				

[1] $\frac{\text{Seeds per lb. X germination percent X lb. per acre broadcast}}{43560}$

[2] Seedlings of these two species could not be differentiated accurately.

[3] Difference between totals by years not significant.

[4] If 21 grazed plots are excluded, total = 10.7. Footnote 3 applies.

* Difference between aspects significant at 5-percent level.

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U.S.D.A. Forest Service
Research Paper INT-54
1968

FLAMMABILITY OF HERBICIDE-TREATED GUAVA FOLIAGE

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah 84401

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This research was partially supported by the
Advanced Research Projects Agency
Department of Defense
ARPA Order 818

This document has been cleared for open publication

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FLAMMABILITY OF HERBICIDE-TREATED GUAVA FOLIAGE

C. W. Philpot and R. W. Mutch

Fire is one of the most economical and effective means of clearing land. Tropical forests are difficult to burn, due to the adverse environment, rapid decomposition of dead fuel, and high moisture content of the vegetation. Herbicide treatments to kill the trees and provide a more flammable fuel continuum have been suggested. Such treatment will lower the moisture content of the leaves, add to the surface fuels if abscission occurs, and possibly change the chemical composition of the plant material. We have determined some of the chemical changes and changes in flammability of guava leaves (Psidium guajava L.) treated with 2,4-D and 2,4,5-T in Puerto Rico.

The major components of natural fuel are cellulose, usually amounting to 40-45 percent by weight, lignin, 30 percent, and hemicelluloses, 25 percent. Lignin does not undergo pyrolysis below 400° C. Above this temperature the reaction is quite slow(6).[1] Therefore, lignin is probably not very important from a pyrolytic standpoint although it contributes to the glowing reaction. Cellulose makes up approximately 65 percent of the lignin-free fuel, and its pyrolytic mechanisms should have great influence on the way the fuel burns.

The pyrolysis of cellulose can be represented as taking place along two pathways (4). The low temperature pathway leads to CO, CO_2, H_2O, char, and the glowing reaction. The high-temperature pathway leads to about 30 volatiles and the flaming reaction (5). Treatment of cellulose with inorganic contaminants favors the low temperature pathway and a reduction in flammable volatile production[2] (2, 3). Therefore, inorganic compositional changes in natural fuels could affect pyrolytic and combustion characteristics.

In addition to the above-mentioned pyrolytic compounds, nonpyrolytic compounds also exist in natural fuels. These include terpenes, resins, oils, and waxes; they can be quantified by extractive content. The heat content of these extractives is about 8,000 cal./g. as compared to the fuel, which has approximately 4,400 cal./g. The majority of these compounds volatilize at temperatures considerably lower than 200° C. Variations in extractives should lead to variations in rate of energy release during burning and possibly to changes in rate of spread.

We measured the ash content, ether extractives, and high heat content of treated and untreated guava leaves. The fuels were then subjected to thermogravimetric analysis (TGA), differential thermal analysis (DTA), and small-scale burning tests. This presents the results of these tests.

Methods

The guava was sprayed with a mixture of 12.5 lbs. acid equivalent of 2,4-D and 12.8 lbs. acid equivalent of 2,4,5-T per acre. This was applied as 3 gal. herbicide plus 7 gal. diesel oil per acre. Samples of treated dead leaves, untreated dead leaves, and living foliage (designated in this paper "treated," "dead," and "green," respectively) were collected in Puerto Rico, air-dried, and shipped to the Northern Forest Fire Laboratory, Missoula, Montana.

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[1] Numbers in parentheses refer to Literature Cited.

[2] Shafizadeh, F. Pyrolysis and combustion of cellulosic materials. Advances in Carbohydrate Chemistry 23: 419-474, 1969. (In press.)

Subsamples were taken, ground to 40 mesh, and used for analysis. Ash content, diethyl ether extractives, and high heat content were determined using standard procedures.[3] Three replications of DTA and TGA were performed on a DuPont Model 900 thermal analyzer. The N_2 was 99.98-percent pure by volume. The TGA was run on 10-mg. samples in air or N_2 at 100 cc./min. with a heating rate of 15° C./min. The DTA was run on approximately 5-mg. samples in an N_2 atmosphere, with flushing at 1 liter/min. and heating at 15° C./min., using SiO_2 for reference.

A 60-g. sample (dry weight) of the whole leaves was burned in 0.5-sq.ft. circular fuel beds under controlled conditions. The combustion facilities have been described previously (1). The dry-bulb temperature was 85° F. and the relative humidity 22 percent. The bed was burned by igniting 1 ml. of acetone placed in the center of the fuel. Weight loss was recorded over time with a small weighing platform connected to a 10-lb.-capacity Statham load cell. The output was fed through a voltage divider and into a Bausch and Lomb millivolt recorder (fig. 1).

Figure 1.--Small burning test in controlled environment using a 0.5-sq. ft. circular fuel bed.

[3] American Society for Testing Materials. D1108-56--Ether solubility of wood; D1102-56--Method of test for ash in wood; D2015-66--Method of test for gross calorific value of solid fuel by the adiabatic bomb calorimeter. ASTM Standards.

Results

The results of the chemical analysis are presented in table 1. The treated fuel was lowest in ether extractives, highest in ash content, and lowest in heat content. The values for ash content of the dead fuel fell between the treated and green. The dead fuel was highest in extractives and heat content.

The TGA and DTA indirectly showed the treated fuel to be less flammable. The cellulose endotherm (325° C.) and exotherm (360° C.) on the DTA were of the lowest magnitude for the treated fuel; the endotherm occurring at 215°-220° C. and the exotherm occurring at 280° C. were also the smallest for the treated fuel (fig. 2).

The TGA in N_2 (fig. 3) showed consistent differences between the three fuels. The treated fuel resulted in the highest residue at 450° C., the lowest maximum weight loss rate, and the smallest weight loss from 200° to 375° C. The TGA in air also showed the lowest maximum weight loss rate (fig. 4) for the treated leaves. The dead fuel underwent ignition at about 350° C., but the treated fuel did not ignite until after 440° C. However, no ignition tests were performed to check these phenomena.

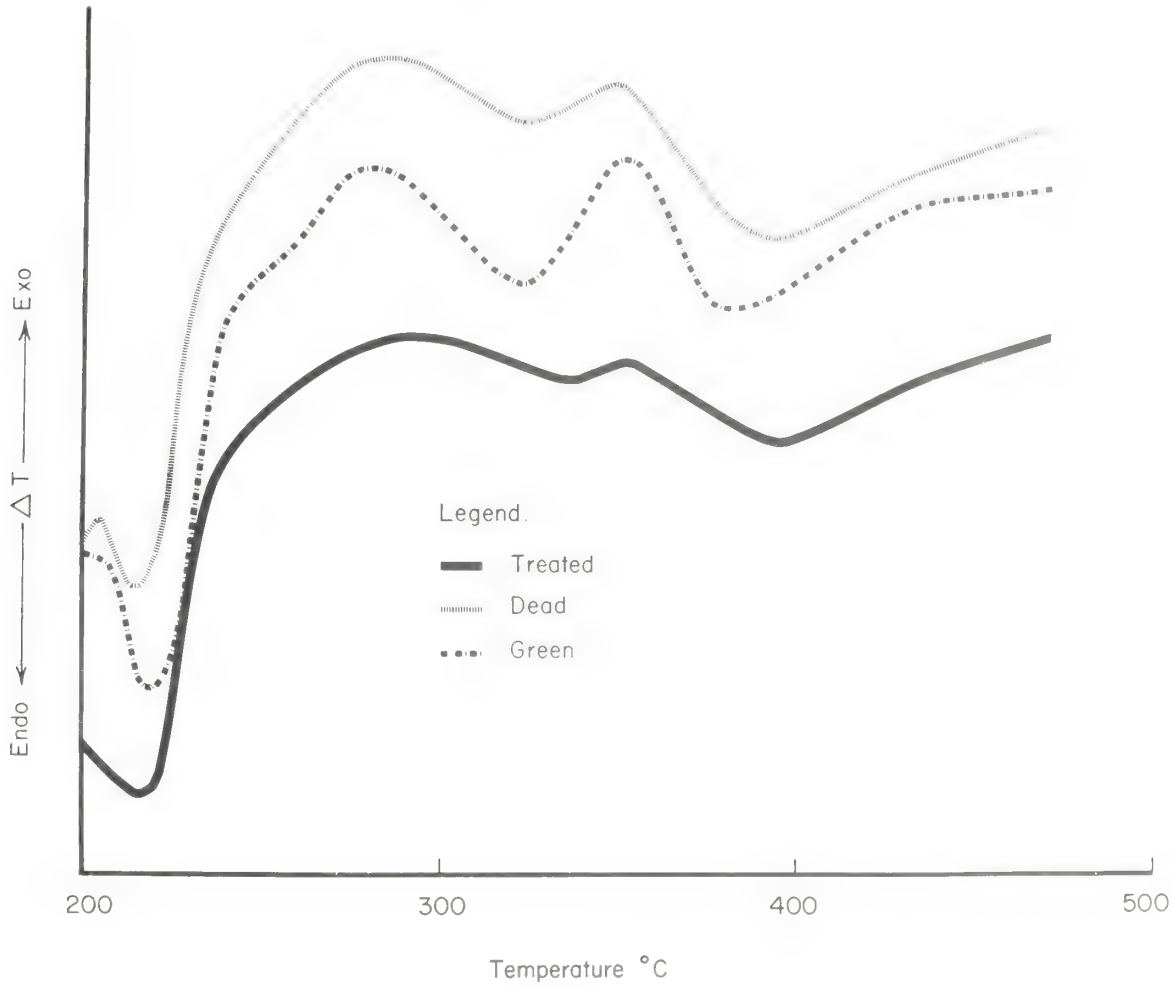


Figure 2.--Results of DTA for guava leaves showing relative magnitude of changes due to treatment. Ordinate zero position is displaced for curve separation.

Table 1.--Analysis of guava foliage

Item	Treated	Dead	Green
Ash content (percent dry weight)	7.79	6.24	6.08
Ether extractives (percent dry weight)	7.60	9.22	8.65
Heat content (cal./g.)	4,495	4,656	4,582
Extracted fuel heat content (cal./g.)	4,200	4,389	4,345
Ashless residue at 450° C. (TGA-N_2) (percent)	37.2	35.8	34.4
Weight-loss rate--max. (TGA-N_2) (percent)	0.38	10.42	0.40
Weight loss 175°-350° (TGA-N_2) (percent)	42	44	46
Weight-loss rate--max. during burning (percent)	1.55	2.00	1.80

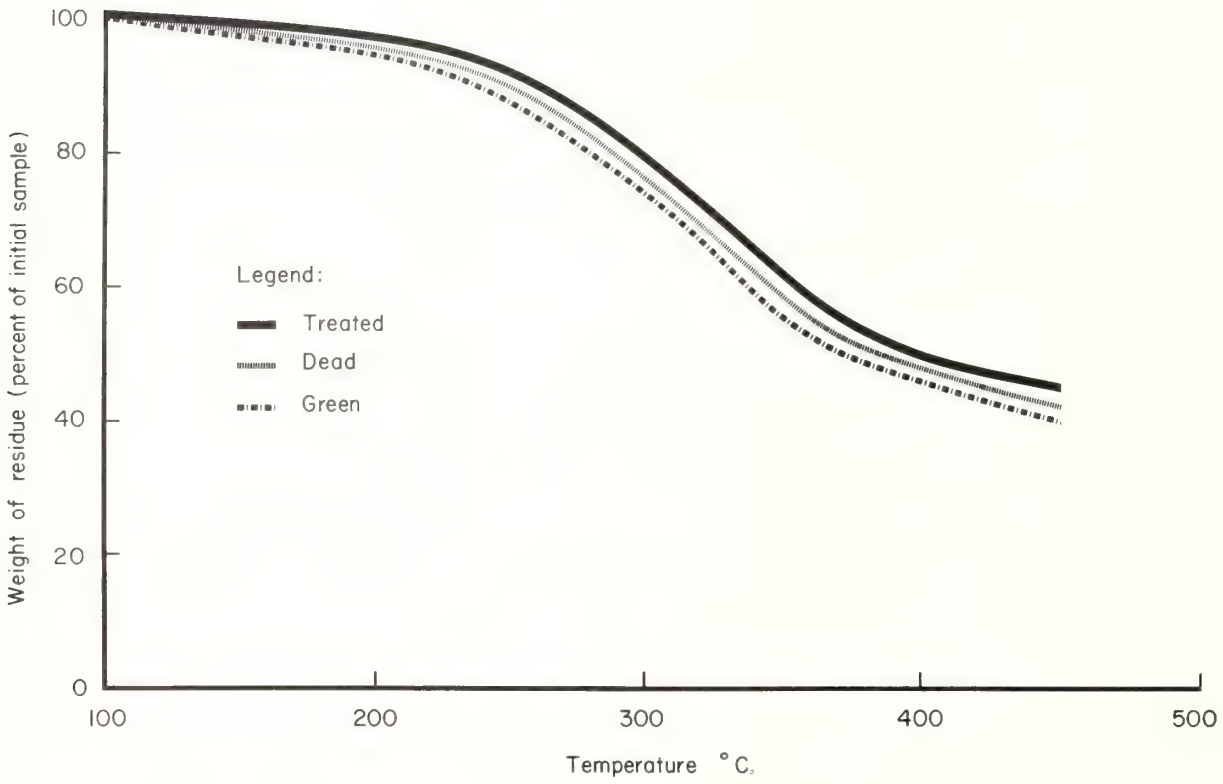


Figure 3.--Results of TGA for 10-mg. samples in N_2 show the effect of fuel treatment. Most rapid weight loss and lowest residue may indicate highest flammability.

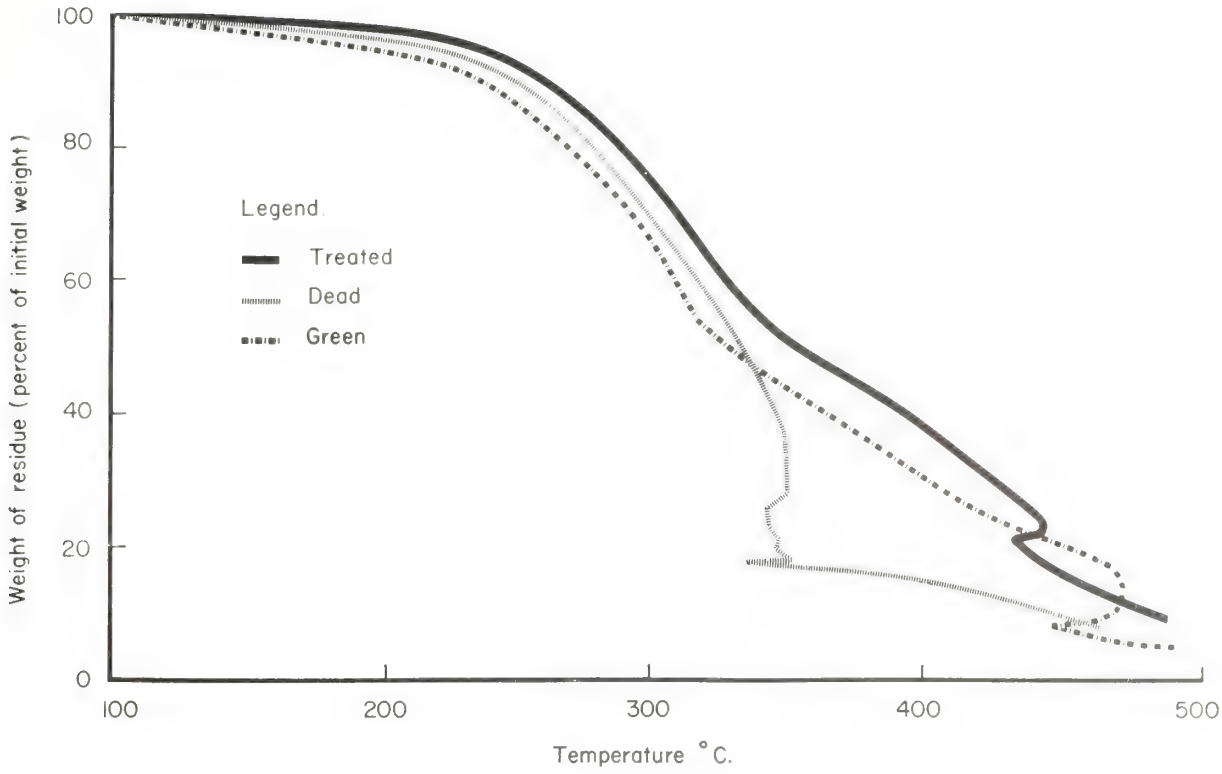


Figure 4.--TGA curves in air for guava with an initial sample of 10 mg.

Small-scale burning tests also showed the treated fuel to be the least flammable. The weight-loss curves are shown in figure 5. Maximum and average weight-loss rates were lowest for the treated fuel. The rate of weight loss and rate of energy release are presented in figures 6 and 7. The energy-release rate was computed by multiplying weight loss and heat content. The relationships of the curves in the two figures are not identical because the heat content of each fuel is different. This difference accentuates the differences in burning rates of the three fuels. The assumption that heat value remains constant during burning is not valid, but it probably can be used in this comparison among treatments.

Discussion

The herbicide treatment apparently changed three parameters of the foliage: the heat value decreased, ether extractives decreased, and ash content increased. These changes reduce the flammability of the treated sample.

The decreased heat value of the treated foliage is due to a reduction in the amount of ether extractives and a reduction in the heat content of the extracted fuel. The average heat contents of green and dead extracted fuel differ by only 44 cal./g., or less than 0.6 percent. The heat content of the treated extracted fuel is about 150 cal./g. lower than the other two. This difference might be due to a more rapid decomposition of the treated foliage, with accompanying reduction in heat content level. The mass change associated with decomposition would also help to account for the high ash content of the treated sample.

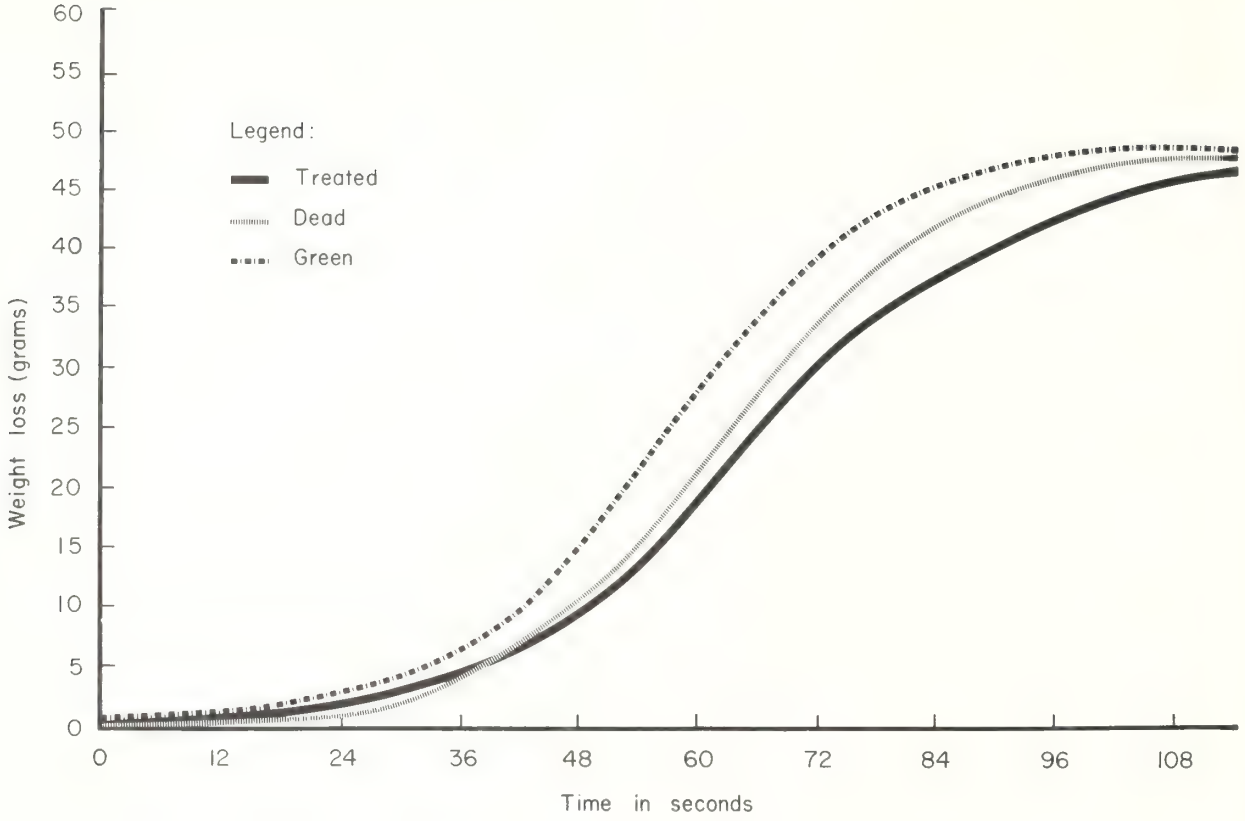


Figure 5.--The weight-loss curve for the small-scale burning tests.

High ash content of the treated leaves corresponded with a decrease in the pyrolytic rate and an increase in residue, or a reduction in volatile production. The cellulose endotherm and exotherm in the DTA analysis were smallest for the treated leaves. Similar results are observed when pure cellulose is treated with inorganic contaminants (2). Apparently the cellulose in natural fuel responds to treatment in the same way as pure cellulose. However, in tests of the treated leaves, the temperatures at which pyrolysis occurred did not change with treatment as they did in tests of cellulose.

The results of the small-scale burning tests tended to agree with those of the TGA curves in N_2 and air. The maximum and average weight loss rates and energy release rates were lowest for treated foliage and highest for dead foliage. The differences between treatments seem to be greater in the burning tests. This could be due to the effects of the nonpyrolytic volatiles on the combustion rate. Extractives would have little effect on the TGA curves because they volatilize well below 200° C.

Conclusions

1. Herbicide-treated foliage of guava had a higher ash content and a lower ether-extractive content than green leaves or naturally killed leaves.

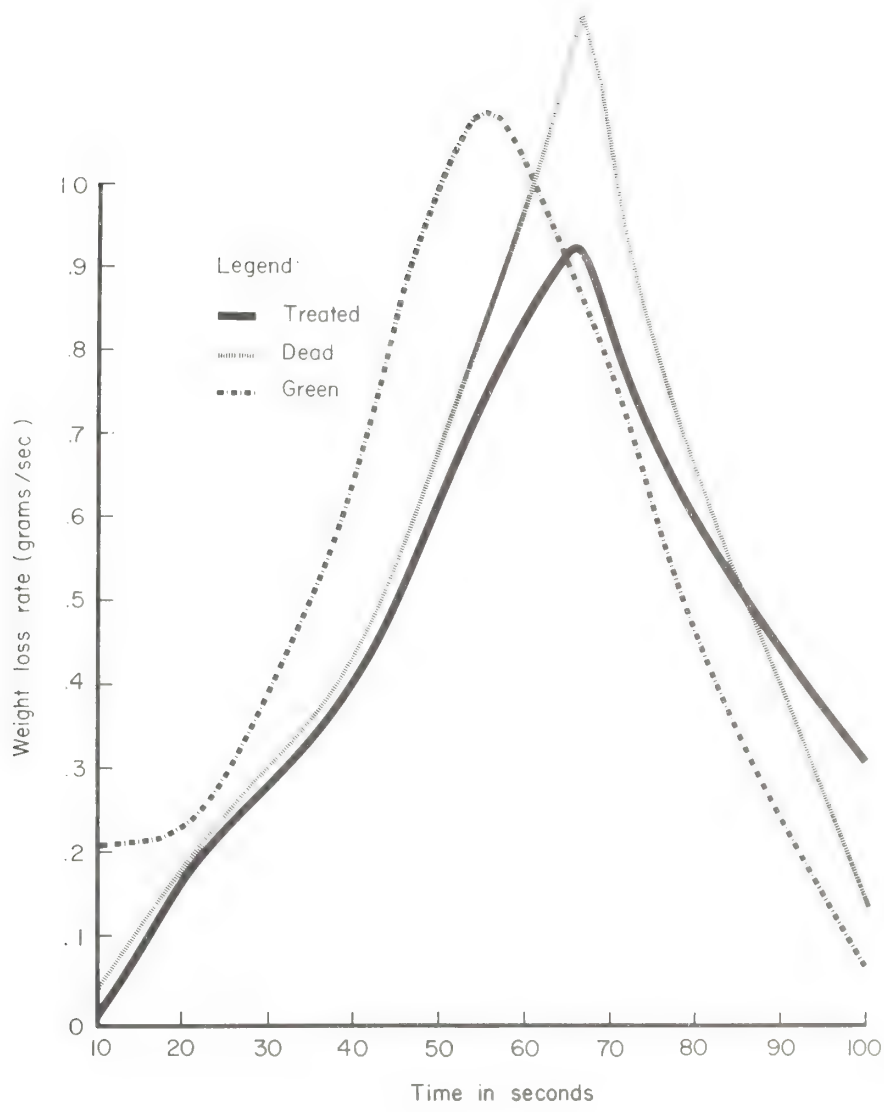


Figure 6.--The weight-loss rate for guava from the small-scale burning tests.

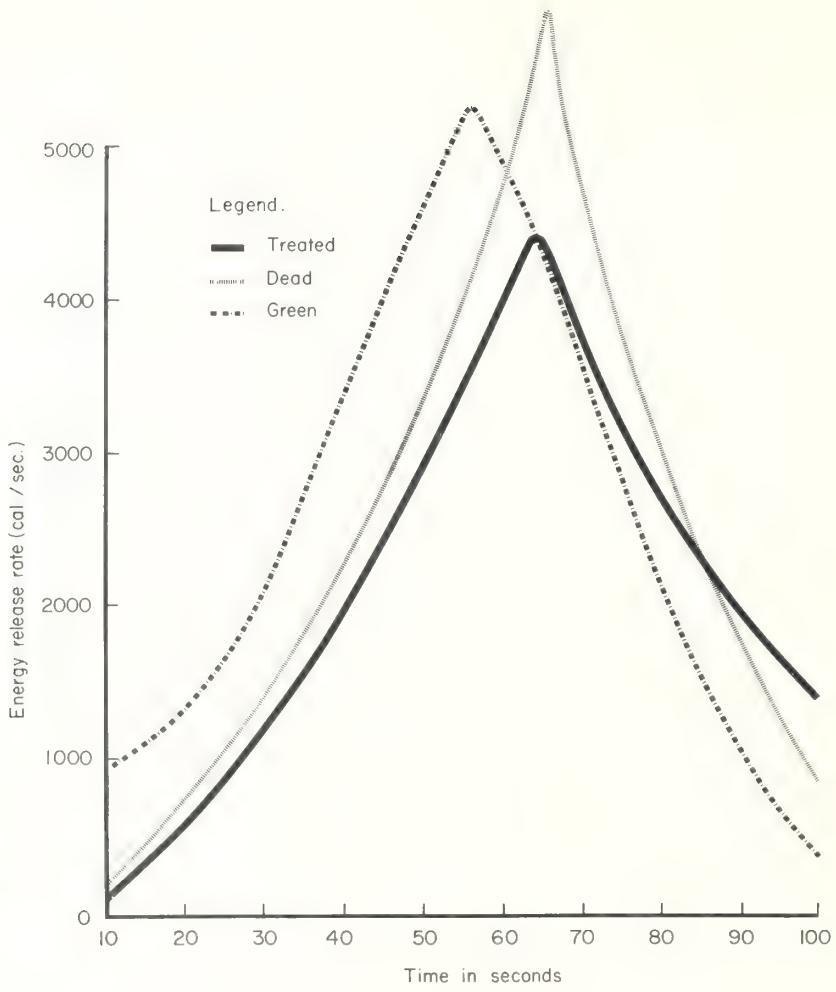
2. The higher ash content of treated leaves affected the TGA curves, reducing the weight-loss rate and increasing the residue at 450° C. This means less volatiles were produced by the treated fuels. The DTA of treated leaves showed a reduction in endotherm and exotherm intensity.

3. The increase in ash and/or the decrease in extractives reduces the burning rate of guava.

4. This study gives support to the possibility of using TGA to replace the more complicated and time-consuming burning tests.

5. Treatment of guava with 2,4-D and 2,4,5-T does not increase flammability with respect to naturally killed foliage, environmental conditions being equal. The herbicides kill the leaves and reduce their moisture content, making them more flammable than living leaves; however, no pyrolytic advantage is gained because of induced

Figure 7. --The energy-release rate for guava from the small-scale burning tests.



chemical changes. Guava is probably not highly flammable in the first place because of its high mineral content.[4] The TGA residues, as compared to those of highly flammable species, substantiate this.

6. The herbicide probably increases the decomposition rate, leading to a higher ash content on a dry-weight basis because of the mass change. The extractives may be degraded by herbicidal treatment also.

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FACTORS THAT AFFECT THE SINGLE-FAMILY HOME MARKET FOR WOOD WINDOWS

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U.S.D.A. Forest Service
Research Paper INT-55
1968

FACTORS THAT AFFECT THE SINGLE-FAMILY HOME MARKET FOR WOOD WINDOWS

Robert E. Benson

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Joseph F. Pechanec, Director

HIGHLIGHTS

- About half the windows used in new single-family homes are wood, but this varied widely among cities, depending on geographical location.
- Maintenance requirements and performance characteristics account for much of the geographical differences in the use of wood windows.
- Builder is the principal decision maker in selecting windows used, but home buyers and suppliers influence his choice.
- Style and architecture of the home determine the type of windows used, but not the material.
- Appearance of wood windows is a major factor favoring their use.
- The cost for wood windows is higher than that for aluminum windows and wood windows are used more extensively in higher priced homes.
- Market outlook for wood windows depends upon such factors as trends in price and design of homes, reduced maintenance for wood windows, and relative costs of aluminum and wood windows.

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INTRODUCTION

Millwork products represent one of the volume uses for the Nation's timber resources, particularly soft-textured softwoods. In 1960 the millwork industry used over 1.5 billion board feet of lumber, of which 46 percent was ponderosa pine and 10 percent other softwoods, such as white pine, cedar, sugar pine, and redwood. Besides utilizing some of the more valuable species and grades of softwood lumber, this industry generates considerable income and employment since multifaceted assembling, shaping, and marketing activities are involved in the production and distribution of most millwork products. In 1963, the value of millwork products was $1.3 billion, an increase of 21 percent over 1958.

An appraisal of the market outlook for these products is vital to planning for both the industry and for managers of timber resources. The harvest of old-growth timber and the regulation of species and wood quality in young stands to meet the demand for wood suitable for millwork can best be accomplished when expected market trends are defined accurately. To do this, it's necessary to make product surveys of various segments of the construction market in which the millwork industry competes --doors, exterior siding, cabinets, windows, etc. This report presents the results of one such survey--the current use of wood windows in new single-family dwellings.

Wood windows account for over 10 percent of the value of millwork products. Between 1958 and 1963, the value of shipments of wood windows increased only slightly, whereas the actual number of wood windows sold declined. Before World War II, most of the windows used in residential construction were wood, but during the 1950's aluminum windows captured a large part of the market. Recently, this trend has apparently reversed, for the use of wood windows is increasing, at least in some segments of the market.

Although no comprehensive data are available, studies and estimates indicate that wood windows probably comprise about 50 to 60 percent of the windows currently being installed in new single-family homes, which account for a large segment of the total market for wood windows. It should be borne in mind that demand in other segments of this market--such as apartments and light commercial buildings--may be significantly different from demand in the single-family home market.

This study pertains only to windows used in 7,920 single-family homes built either in 1965 or 1966, depending upon which year the builder was interviewed. The 92 builders interviewed were all located in 20 cities that were chosen at random from metropolitan areas with populations over 100,000.

The specific objectives of the study were to

1. Determine wood windows' share of the market and identify geographic and other variations in their use.

2. Determine the relative importance of the homebuilder, home buyer, and the supplier in selection of windows.

3. Identify and evaluate the importance of influences on choice of windows, such as

   * Maintenance requirements and other performance characteristics
   * Appearance
   * Availability and suppliers' services
   * Style and price of home
   * Costs
   * Home buyers' preferences

4. Determine the degree to which wood windows meet the more important market requirements, and what changes in manufacturing or distribution are needed.

5. Appraise the market outlook for wood windows.

VARIATIONS IN USE OF ALUMINUM AND WOOD WINDOWS

About 48 percent of all windows used by builders in this study were wood; the remaining were aluminum.[1] The use of wood windows varies geographically, however, as shown in figure 1. Wood windows predominate in cities in the North and East and were used least in cities in the South and West.

Builders don't necessarily limit their use of windows in a house to one material. In 15 percent of the houses, for example, builders used both--usually wood windows on the front of the house and aluminum on the sides and the rear. In 40 percent of the houses, wood windows were used primarily; that is, all or nearly all of the windows in the house were wood. In the remaining 45 percent, aluminum windows were used primarily.

The use of wood windows also varies with the sale price of the house. Table 1 shows that wood windows were used primarily in only 21 percent of the houses priced under $20,000, compared to 57 percent in homes priced over $30,000. The difference in wood window use between price classes was greatest in cities where neither wood or aluminum predominate; that is, where 25 to 75 percent of all windows used were wood.

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[1]Based on the percent of wood and aluminum windows used by each builder weighted by the number of houses he built.

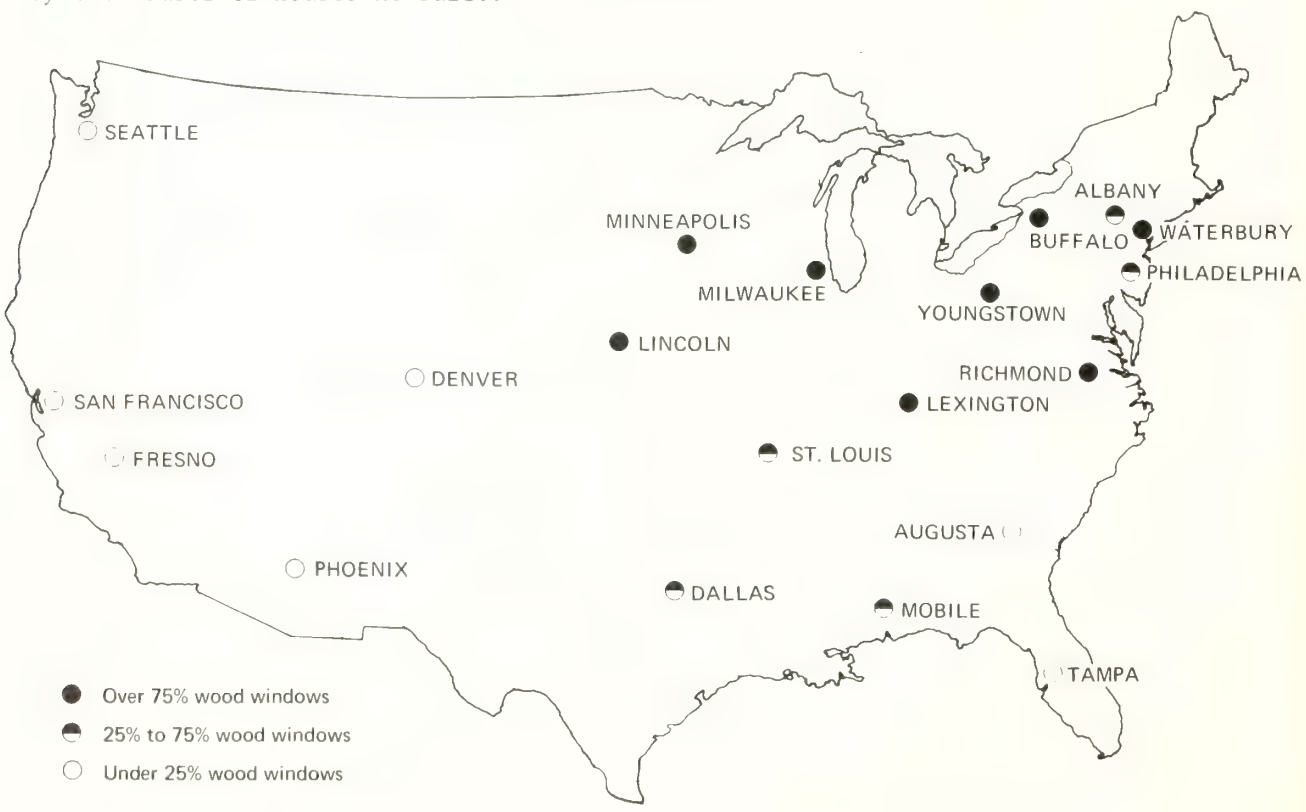


Figure 1.--Window material used in new single-family houses in sample cities.

Table 1.--Window material used by sale price of the house
(Percent of houses)

Primary[1] window material in house	Sale price class of house			
	Under $20,000	$20,000-$30,000	Over $30,000	All price classes
Cities where over 75% of all windows were wood[2]				
Wood	86	100	100	97
Aluminum	14	--	--	3
Both	--	--	--	--
Cities where 25% to 75% of all windows were wood[2]				
Wood	6	40	89	36
Aluminum	60	23	--	31
Both	34	37	11	33
Cities where less than 25% of all windows were wood[2]				
Wood	5	6	5	6
Aluminum	95	89	93	91
Both	--	5	2	3
All cities				
Wood	21	46	57	40
Aluminum	64	37	38	45
Both	15	17	5	15

[1]Wood = all or nearly all windows in the house were wood; aluminum = all or nearly all windows in the house were aluminum; both = both wood windows and aluminum windows used.

[2]See map, figure 1, for cities sampled.

Figure 2.--In moderately priced homes such as this one under construction, aluminum windows are often favored because their installed cost is low and they need no painting.

FACTORS THAT DETERMINE BUILDERS' CHOICE

Builders take into account not one but several factors when selecting windows to use in their houses. These vary in importance among individual builders as shown in the following tabulation.

Factor	Most important (Percent)	Second most important (Percent)	Third most important (Percent)
Appearance and architectural style	32	4	15
Purchase price of window unit	21	19	8
Home buyers' preferences	15	12	7
Performance	9	19	16
Price of house	8	12	4
Maintenance requirements	5	14	16
Installation and finishing cost	5	8	7
Availability and supply services	1	3	4
Other	4	5	5

Figure 3.- Wood windows require proper paint maintenance. Windows in this 9-year-old house had not been repainted since installing, and the paint is now weathered and peeling.

MAINTENANCE AND PERFORMANCE

Much of the geographic variation in wood window use can probably be attributed to the maintenance requirements and performance characteristics of wood windows compared to those of aluminum windows.

Maintenance requirements is a chief factor favoring aluminum windows. In cities where aluminum windows predominate--less than 25 percent wood windows--many builders commented that aluminum is "maintenance free" or that "wood windows need frequent repainting." These comments were made most frequently in hot, dry areas of the West. In cities in other areas, such comments were fewer, although some favored aluminum because of the "no repainting" feature, while others favored wood, claiming wood windows were easier to repair and adjust. The comments on window maintenance are summarized in figure 5.

Wood windows are favored because of their insulating qualities and for being condensationfree, particularly in cities where wood predominates and in cities where neither wood nor aluminum predominate (fig. 6). Typical comments from builders in these cities were that wood windows are "warmer" or "condensationfree" or that aluminum windows "are cold," "weep," or "frost up." These factors are apparently less important to builders in warmer areas, as only a few builders in cities where aluminum predominates commented on insulation and condensation.

Builders also commented on proper fit and ease of operation (fig. 7). Some builders feel that it is the quality of the window and the weather stripping used rather than the window material that determines fit and operation. This may account for the

Figure 4.--Excessive pitch in the wood from which this window was manufactured caused this problem on a 3-year-old house. Note that paint on adjacent window sash is in good condition.

fact that opinions were about equally divided as to wood or aluminum having the advantage in fit and operation. Some builders felt that wood windows fit better; other builders that large-size aluminum sliders tend to stick because they are not as stout as wood. On the other hand, some reported that wood windows stick during humid weather and fit too loosely during dry spells. In western cities, builders' concern is over dust leakage, whereas in northern cities it centers on cold air leakage during the winter.

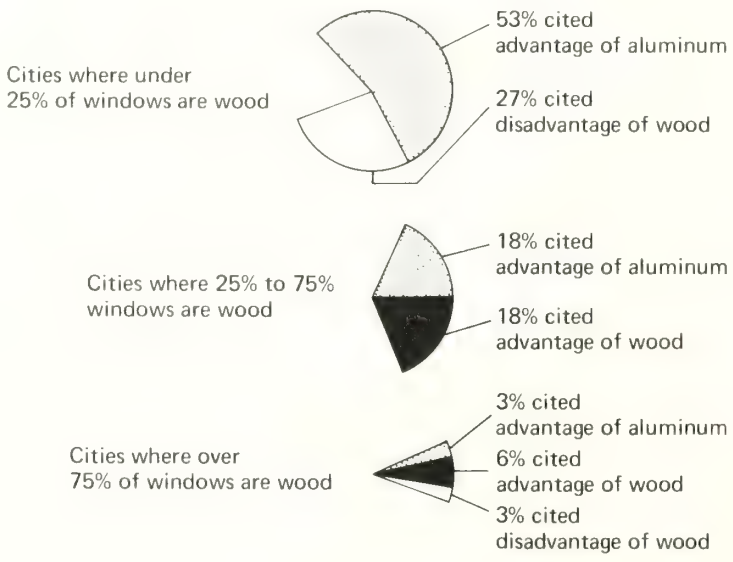

Cities where under 25% of windows are wood
53% cited advantage of aluminum
27% cited disadvantage of wood
Cities where 25% to 75% windows are wood
18% cited advantage of aluminum
18% cited advantage of wood
Cities where over 75% of windows are wood
3% cited advantage of aluminum
6% cited advantage of wood
3% cited disadvantage of wood

Figure 5.--Builders' comments concerning maintenance.

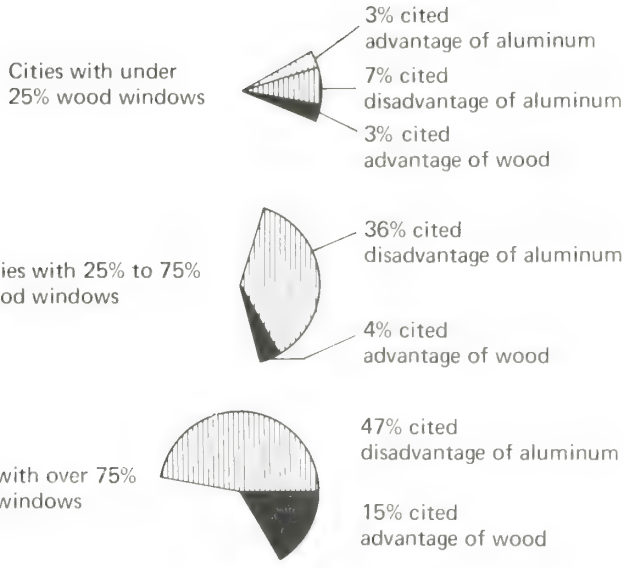
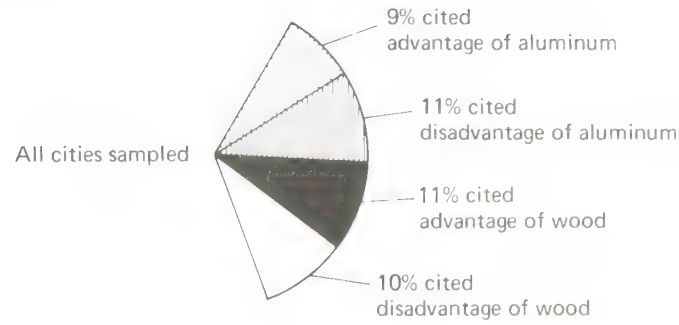

Cities with under 25% wood windows
3% cited advantage of aluminum
7% cited disadvantage of aluminum
3% cited advantage of wood
Cities with 25% to 75% wood windows
36% cited disadvantage of aluminum
4% cited advantage of wood
Cities with over 75% wood windows
47% cited disadvantage of aluminum
15% cited advantage of wood

Figure 6.--Builders' comments concerning insulation and condensation.

Figure 7.--Builders' comments concerning proper fit and ease of operation.


All cities sampled
9% cited advantage of aluminum
11% cited disadvantage of aluminum
11% cited advantage of wood
10% cited disadvantage of wood

APPEARANCE AND ARCHITECTURAL STYLE

Style of the house is a primary consideration to builders in choosing types of windows--double hung, awning, etc. (table 2). However, since most of these window types are available in either wood or aluminum, house style does not directly determine whether wood or aluminum will be used. Double-hung or single-hung windows are used most often in traditional (colonial, provincial, etc.), ranch, and rustic homes. Awning, casement, or sliders are most common in contemporary houses. No attempt was made to determine how many houses of each style were built.

Table 2.--Type windows used in different style houses by builders sampled

(Percent of builders)

Type window	Traditional	Ranch and rustic	Contemporary
Double hung or single hung	92	56	14
Awning or casement	4	33	59
Slider	--	11	22
Fixed	4	--	5

Figure 8.--Double-hung wood windows are favored in traditional style houses such as this one, called "the Farmhouse."

Although style of house does not directly determine window material, some builders favor wood windows for creating an "authentic" effect in traditional and rustic-style houses. About one-fourth of the builders commented that wood had good appearance or that aluminum lacked good appearance; most of these were in northern and eastern cities. However, in western cities, a few builders who used wood windows indicated they did so primarily because of appearance. One builder who used aluminum windows with a baked-on white finish felt these had good appearance because "they look like wood."

BUYERS' INFLUENCE

Builders know what type windows are preferred in their markets and usually plan accordingly. Buyers are frequently given some options in windows to be installed, but most builders indicate that buyers either "go along" with the windows shown in the model home or plans, or they ask the builder for advice. The builder thus can steer the buyer to the window he prefers. The options offered by builders are:

	Percent of builders
Option of both type and material	35
Option of any type of wood windows	10
Option of any type of aluminum windows	4
Options in glazing, hardware, etc., but not type or material	2

Figure 9.--Windows are used to enhance the style, appearance, and sales appeal of the house. This wood window has a fixed center sash flanked by casements sash with diamond-pattern grilles.

About one-third of all the builders offer buyers the choice of either wood or aluminum windows. In cities where aluminum windows predominate, wood windows are usually offered at extra cost, or are limited to higher priced homes. Several builders in cities where wood windows predominate indicated that they charge extra for aluminum windows; furthermore some told buyers that they would not be responsible for the performance of aluminum windows.

About one-third of builders feature windows in their sales promotions. Another one-third indicate that even though they don't specifically base their sales "pitch" on windows, they are careful to use windows that create a good impression and are accepted in the market area.

In their selling, builders stress the strong points of the windows they use. Builders using wood windows stress insulation, appearance, and quality (including brand); builders using aluminum windows stress low maintenance, and a few builders stress convenience features, such as insulating glass (no need for storm sash) and snap-out grilles (easy cleaning).

COSTS

About two-thirds of the builders indicated that window costs--either purchase price or installed and finished costs--are highly important. To some extent, this is reflected in type of windows used: aluminum units, which generally cost less than wood, are used more extensively in lower priced homes where costs are often more critical. However, this doesn't mean that builders are using the lowest cost windows available.

The average costs for window units is shown in table 3. The size and quality of windows used varied among builders, but costs were made as comparable as possible by not including combination windows, or storm sash, screen, insulated glass, and similar accessories. Costs for cleanup and callbacks are also excluded because these were reported by too few builders to derive meaningful averages.

The costs of labor (installation and finishing) varied widely among individual builders even within the same city. In part this is because of differences in cost accounting and allocation procedures. A more detailed analysis might alter these figures. However, these averages are useful to the extent they indicate what builders think their costs are, which is significant from the standpoint of decisionmaking and opinions on window costs.

Table 3.--Average cost of windows by type of window used by builders in single-family houses

Item	Wood double hung	Wood casement, awning, and hopper	Aluminum single hung, double hung	Aluminum glider	Aluminum casement, awning, and hopper
			Dollars		
Purchase price[1] (unit and trim)	22.96	35.97	19.54	20.09	21.50
Installation (unit and trim)	5.46	3.90	3.45	3.50	3.00
Painting	6.68	2.00	--	--	--
Total installed cost	35.10	41.87	22.99	23.59	24.50
Number of builders[2]	43	8	14	17	5

[1]Does not include storm, screen, or similar accessories.
[2]Indicates number of builders who cited their most commonly used window unit. Some of these did not provide complete cost information for the unit.

Purchase price.--The purchase price of double-hung wood windows averages about 15 percent higher than that of similar aluminum windows. In some other window types, the price differential is greater. The difference in purchase price does not appear to influence most builders' choice of material, however. Over one-third of the builders cited the price advantage of aluminum windows over wood, but less than 10 percent used aluminum windows in areas where wood windows predominate.

Installation and finishing.--The cost of installing wood windows is somewhat higher than that for aluminum. Installing the trim on wood windows accounts for as much as half the total installation cost. This accounts for much of the cost difference between aluminum and wood windows since trim is not usually used with aluminum. Aside from trim, there is apparently little difference in installation. Some builders feel aluminum windows can be installed faster than wood windows. However, other builders feel aluminum windows are more prone to damage during construction (glass breakage and bent frames).

Finishing accounts for almost 20 percent of the total installed cost for wood double-hung windows. The cost of finishing is considerably less for other types of wood windows because they do not usually have grilles (bars or muntins) as do most double-hung windows.

Preprimed wood units.--Builders' opinions on preprimed wood units vary. The chief advantage cited is the protection provided by prepriming during construction. The chief complaints are that prepriming is of poor quality--either too thin or too chalky--and that painters would not assume responsibility for paint on preprimed units. Comments made by builders were:

Figure 10.--Some builders prefer preprimed windows such as this one because the prime coat protects the window during construction.

	Percent of builders
Prepriming protects during construction	15
Preprime of poor quality	8
Prepriming does not allow natural or stained finish	4
Prepriming does reduce overall costs	2
Prepriming does not reduce overall costs	2

AVAILABILITY AND SUPPLY SERVICES

The choice of supplier for windows appears to be largely a matter of individual preference, as the supply source used does not appear to be related to the size of the builder's operation or his geographic location. The following tabulation shows supply sources for windows.

Source	Wood windows (Percent)	Aluminum windows (Percent)
Millwork shop	52	4
Manufacturer	26	63
Retail lumber dealer	9	3
Wholesaler	2	15
Jobber	9	11
Other	2	4

Figure 11.--These fixed windows were custom built at a local millwork shop to fit the specific size and style needs of the house. The sash on the right has patterned glass that admits diffused light.

Good delivery service, discounts, credit arrangements, and technical services are all part of the supply package builders expect and get from their suppliers. Most builders purchase their windows from a single supplier and to this extent their choice of windows is influenced by the brands and types he carries.

About 10 percent of the builders complained that there is a long delay when ordering stock wood windows. This requires that builders order their windows well ahead of time (in some cases 30 days or more). Others complained that their supplier did not carry a complete stock of sizes in the brand and type of window they wanted, and several others said that they could not depend on getting preprimed wood windows. These few comments were random and included all geographic areas, large and small builders, and several different types of suppliers.

About one in four builders used some custom-made windows in their homes. Most of these were custom arrangements of standard windows (fig. 12). Generally the builder's regular supplier assembled these custom windows.

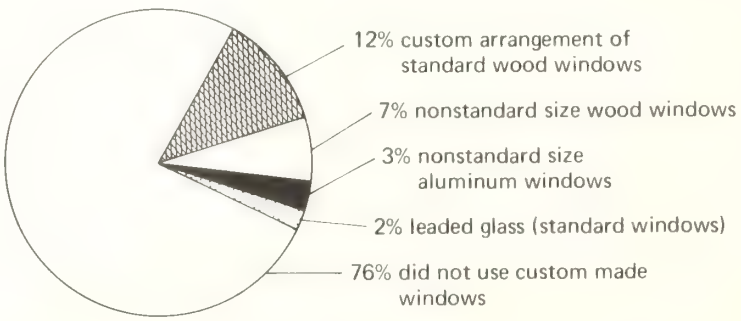

12% custom arrangement of standard wood windows
7% nonstandard size wood windows
3% nonstandard size aluminum windows
2% leaded glass (standard windows)
76% did not use custom made windows

Figure 12.--Builders who used custom-made windows.

Figure 13.--A growing market for luxury homes such as this one is favorable to wood window use. Some designs use fixed windows extensively; the portion of the house shown has only two operating window sash.

MARKET OUTLOOK

Current trends in the home construction market could result in builders making basic changes in their window-buying policies in the immediate future; specifically (1) the continued increase in the installation of air conditioning in single-family homes; and (2) the expected growth of the "luxury home" market.[2] In fact, over 20 percent of the builders contacted reported having made such changes in the 2-year period prior to being interviewed. Some, admittedly, involved merely changing brands or suppliers, but many involved window material and type or both.

Several builders reported they had begun buying more wood windows or were anticipating doing so because of the increased demand for higher priced homes (in 1965, one out of eight houses built was priced over $37,500[2]). As pointed out earlier, wood windows are in demand in higher priced houses.

The "better insulation" and "less condensation" advantages of wood windows tie in with the trend toward air conditioning, some builders noted. However, this might be offset by the fact that air conditioning permits the greater use of fixed windows and reduces the need for operating windows, which could alter future market demands both in terms of number of windows used as well as style of windows. In fact, 5 percent of the builders interviewed anticipate that they will be installing not only fewer operating windows but a fewer number of total windows in their houses as the more advanced new home designs win greater market approval.

The growing application of the "baked-on finish" by the fabricators of aluminum products poses a formidable threat to the wood window manufacturers' hopes to retain their selling advantage from the standpoint of "appearance." Similarly, these window manufacturers are designing greater "insulating" qualities in their products. In the face of these developments, it appears that wood window producers are confronted with the problem of improving the "maintenance" qualities of their products and, at the same time, reducing the installed costs. Relative cost is certain to have a greater weight in window buying decisions as differences in appearance and performance features are diminished.

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[2] Practical Builder 31(11) "The Luxury Market" Cahners Publishing Co. November 1966.

Benson, Robert E.

1968. Factors that affect the single-family home market for wood windows. U.S. Dep. Agr., Forest Serv., Intermountain Forest and Range Exp. Sta., Ogden, Utah 84401. 13 pp., illus. (U.S. D.A. Forest Serv. Research Paper INT-55)

A survey of builders in 20 cities throughout the Nation shows wide geographical variations in window materials used in new single-family homes. Appearance, style, price, and performance influence choice and thus contribute to these variations. Current trends in the new single family home market, improvements in window materials, and relative prices of aluminum and wood windows are key factors in the market outlook for wood windows.

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SUNDANCE FIRE

U.S.D.A. FOREST SERVICE RESEARCH PAPER INT-56, 1968
INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
OGDEN, UTAH 84401

THE AUTHOR

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U. S. D. A. Forest Service
Research Paper INT-56
1968

SUNDANCE FIRE: AN ANALYSIS OF FIRE PHENOMENA

Hal E. Anderson

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U. S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

PREFACE

Large forest fires are spectacular, usually destructive, frequently dangerous, but always exciting. Fire research organizations, particularly just after a spectacular wildfire, are often eager to organize mobile research teams to study and document fire behavior. Unfortunately, this approach to the study of wildfire is usually not very productive. There are several reasons why not.

It is very difficult for a researcher to be in the right place at the right time when severe fire behavior occurs. Often he is remotely located on the opposite side of a situation, or access to the area of interest is limited or inefficient. There is always the danger that research personnel will interfere with tactical activities at the fire, primarily in the air. There is generally no effective way to properly instrument an area prior to severe fire behavior, simply because there is not enough time and one cannot predict precisely when or where such events will occur.

The Sundance Fire was unique. Early on September 1, there was already a tremendous concentration of fire organization, supplies, equipment, and manpower in the vicinity because of a number of active project fires. An additional force of competent firefighting personnel was gathering to meet the expected need. The Sundance Fire was being fought by State and local forces but was expected to cause increasing difficulty, and preparations were underway to transfer the fire to the U. S. Forest Service. Accumulative weather buildup was extreme, the fire had a 4-mile exposed front, and the current weather was critical. Suddenly the fire made one tremendous run, increasing in size by more than 50,000 acres in one burning period. Since there are communities at each end of the fire run and a road cutting across the center of it, and because firefighting crews were in the Pack River area preparing for a possible run of the fire, many observers saw portions of this spectacular fire run. The mere fact that the event was limited in time and seen by many people permitted the research team to reconstruct some of its characteristics. Interviews with fire control people, local residents, and a variety of other individuals provided firsthand observational knowledge of what happened. Most observations were subjective, but some included measurements.

The Sundance Fire offered a rather unusual situation for analysis and we think the results, as given in this paper, have a great deal of value. Nevertheless, it must be recognized that similar studies might only be redundant. As long as studies are limited by conventional measuring methods, there is no real assurance that an organized effort to chase large fires would produce equal or better analyses. Certainly the development of remote sensing techniques or instrumentation could change the picture considerably, and might allow for improved data collection on wildfires. We believe that fire analyses are best when applied to special case fires.

There is, of course, some value for the scientist to be gained through observation of wildfires. It sharpens his perspective on the real world and on the problems he is facing. We must be cautious, however, not to expect more than is realistic from observing wildfires, while at the same time, we need to consider improved methods for observing them. This is one way that fundamental and theoretical work now underway in laboratories can be related to real-life conditions in the forest.

ARTHUR P. BRACKEBUSCH
Chief of Northern Forest Fire Laboratory

ACKNOWLEDGMENTS

The author acknowledges with deep appreciation the cooperation and assistance provided by the following persons, each in his special field:

DONALD M. FUQUAY for his leadership in organizing the general approach to the analysis and development of a presentation format.

RICHARD C. ROTHERMEL for his leadership in the fieldwork of gathering data and photographs, and interviewing personnel.

ARTHUR P. BRACKEBUSCH for his background knowledge of the area and experience in fire behavior.

JAMES K. BROWN for his responsible appraisal of the fuel complex and calculations of fuel distribution.

WILLIAM H. FRANDSEN for his capable interpretation of the destruction of the Pack River Bridge and contributions in other parts of the analysis.

DWIGHT S. STOCKSTAD for his consultation on the area and the fire behavior.

ARNOLD I. FINKLIN for his thorough and careful collection and analysis of the meteorological data used in the weather interpretation.

ORVAL W. GASTINEAU, Jr., and ROBERT D. SCHUETTE for their valuable assistance in tabulations, computations, and aerial photo analysis.

BRYAN M. OWEN for his competent graphic rendition of fire phenomena conceptions and preparation of other charts and illustrations.

HERMAN WITTMAN for his assistance in the photographic processing of photographs, graphs, and illustrations.

Personnel of the Priest Lake Timber Protective Association, Kaniksu National Forest, and Division of Fire Control, Northern Region, U.S.D.A. Forest Service for provision of fire logs and maps, interviews and valuable information regarding the area, the timber, and the fire.

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INTRODUCTION

The Sundance Fire in northern Idaho stands as a giant among several big fires in the Northwest during the summer of 1967. The magnitude of this fire resulted from a combination of conditions seldom occurring simultaneously — a prolonged dry period, persistent high temperatures, sustained winds during the fire run, and an uncontrolled 4-mile fire front. These conditions produced a rapidly moving fire that burned over a large area and released an awesome quantity of energy. In a period of only 9 hours this fire traveled 16 miles, engulfed more than 50,000 acres, released millions of heat units, snapped and toppled hundreds of trees, and destroyed much of the storage capacity of the watersheds.

The Sundance Fire started its major run on September 1, 1967, at approximately 2:00 p.m. (1400 P.d.t.) and by 11:00 p.m. (2300 P.d.t.) it had completed the run. Shortly after the major run, personnel from the Northern Forest Fire Laboratory were assigned to the fire staff as fire behavior officers, to predict fire behavior and advise the control teams. At the same time, other NFFL personnel were assigned to a research team responsible for investigating the physical phenomena of this fire and for documenting its historical development. Their investigation was actually a detective job, since only evidence remaining on and near the burned area, eyewitness accounts, and records kept by the various agencies were available for interpreting the events. This paper presents the best estimates of fire phenomena that could be made by the research team, using the available information. The progress of the fire, its intensity, the fuel being consumed, the attendant weather events, and other special conditions were analyzed from a multitude of separate observations gathered from both official sources and individuals.

When a forest fire "blows up," the people directly involved are busy moving equipment, materials, and firefighters to new locations, or planning new attack procedures, and their impressions are often confined to a single area or phase of the fire's activity. In reconstructing the fire's movements, any one person's account would have been of limited value. The magnitude of this fire was such that many different people observed it at many different locations. One of the earliest jobs for the research field team was to interview as many people as possible who had observed or participated in the fire activities on September 1. Interviews from 24 people contributed to the determination of fire front location, rate of spread, type of fire, and energy release rate at specific times.

The investigating team has attempted to sort out the details of a violently eventful period of time and construct from them a coherent account of the phenomena of a particular fire. A general conception of what was happening where and when as the fire progressed is necessary to understanding of the physical phenomena. Therefore this paper begins with a description of the geographical area and a narrative of the movement of the fire. The approach to study of certain major factors in the fire development is then explained, and the values calculated from the data are given in a chronology corresponding to the fire's major run. A more detailed discussion of significant features of the fire then follows, leaving for the appendixes information on methods of calculation and experimental procedures that helped the investigators to draw their conclusions.

THE FIRE AREA

Sundance Mountain, the point of origin for the fire, is on a spur off the Selkirk Divide east of the town of Coolin, Idaho. (Topographic relationships of the fire area are shown in figure 1; see also the foldout map at the back of this paper.) The fire up to September 1 was confined to the lower Soldier Creek (elev. 3,600 ft.) and Lost Creek (4,800 ft.) drainages (fig. 2), which lie west and southwest of Sundance Mountain. On September 1, it progressed northeast up to the Divide, engulfing Jeru Peak (6,394 ft.) and Hunt Peak (more than 7,000 ft.), and skirting south of Gunsight Peak (7,357 ft.). As may be noted in figure 1, the elevation drops from 5,800 ft. at the saddles along the Divide to 3,800 ft. on the Pack River at the north edge of the fire path and to 2,600 ft. at the south edge. Northeast out of Pack River is Apache Ridge, running to the southeast; here the fire path is bounded by Roman Nose Mountain on the north at 7,264 ft. and Dodge Peak on the south at 5,026 ft. Northeast of Apache Ridge the terrain slopes to the southeast and is cut by the major drainages of Falls Creek, Highland Creek, Ruby Creek, and Caribou Creek. The fire ended its run near Snow Peak (more than 4,000 ft.) and worked toward Bonners Ferry, Idaho, down Caribou Creek to an elevation of 2,800 ft.

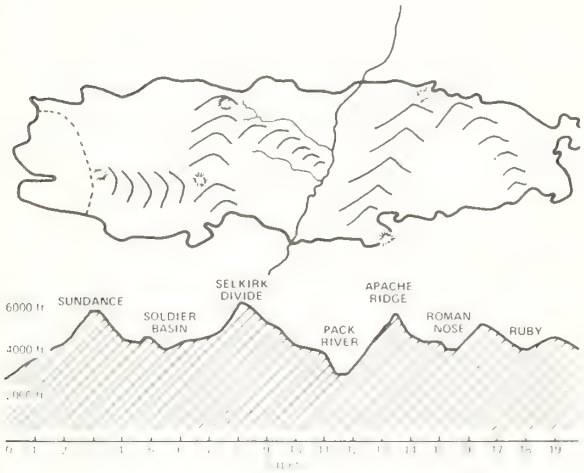
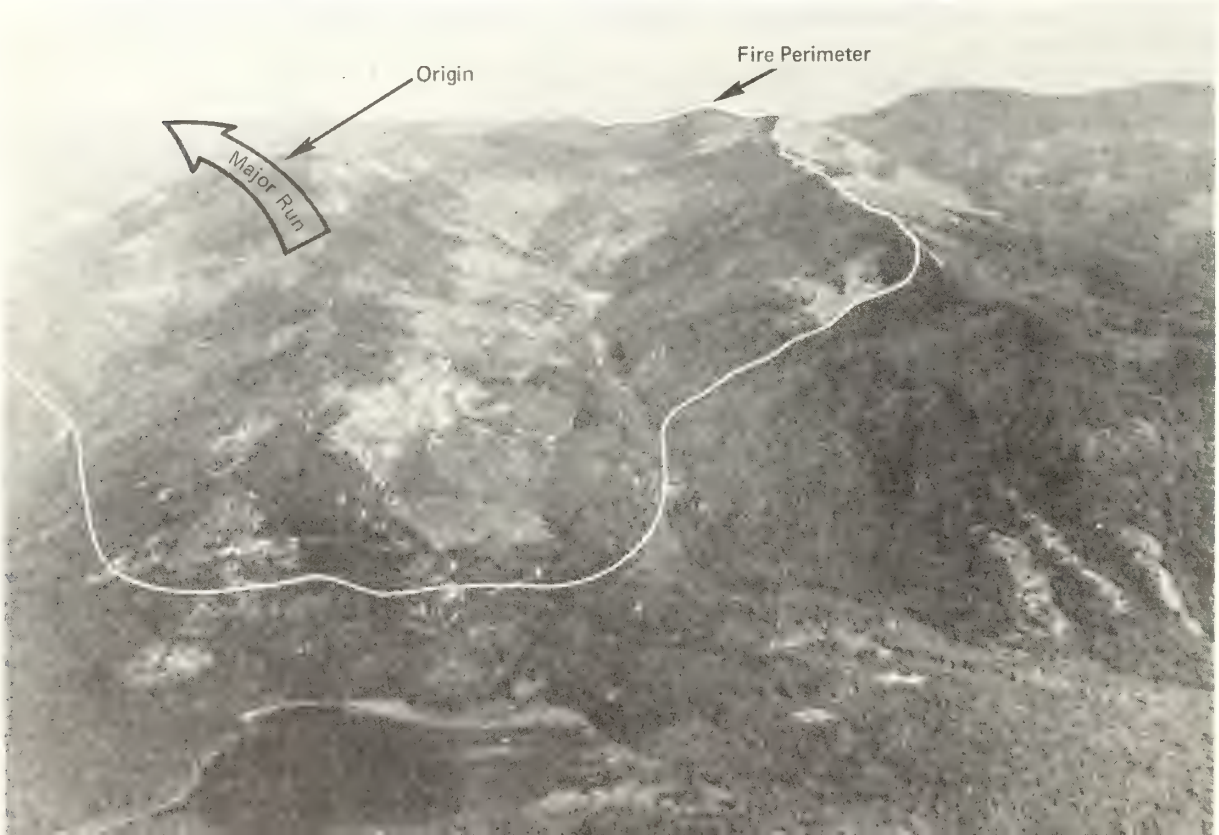


Figure 1. – Topographic diagram of the Sundance Fire area.

Figure 2. – Sundance Mountain, looking to the northeast, with Chase Lake in foreground and Selkirk Divide in near background. Lost Creek is in center and Soldier Creek drainage on left edge.



THE FIRE STORY

THE BUILDUP

The fire story begins in the months before the outbreak itself, in the buildup of fire danger during the summer of 1967. The fire season in northern Idaho developed quite normally, and in the first 3 months showed characteristics of an average fire season. The fire weather records of the Priest River Experimental Forest in northern Idaho, interpreted according to the National Fire-Danger Rating System, illustrate the seasonal buildup of fire danger. The record presented in figure 3 shows the buildup index remaining below the previous record high for the period of 1954 to 1966 until August 11, 1967. The continued buildup in 1967 from late June until mid-September differs from the historical pattern, which has shown one or more breaks in buildup during this period. This year, day by day the situation became more serious, and restrictions were imposed to minimize the hazard of man-caused fires.

Early in August, a high pressure zone had become deeply entrenched over the northwestern United States and was effectively blocking the influx of moist maritime air from the west. No significant amount of precipitation occurred between August 11 and September 1. In the 62 days from July 10 to September 10, only 0.10 inch of rain was measured at Priest River Experimental Forest from four different showers. From August 11 to August 31, the 10-day averages showed the temperatures were the highest, the humidities the lowest, and the fine fuel moisture content the lowest for the season. Relative humidity is estimated to have been below 35 percent continually for at least 72 hours prior to the fire run.

On August 31, all stations in northern Idaho except those at high elevations had buildup indexes rated "extreme." Late on that day, a Pacific weather system was approaching the Washington coast. A warning

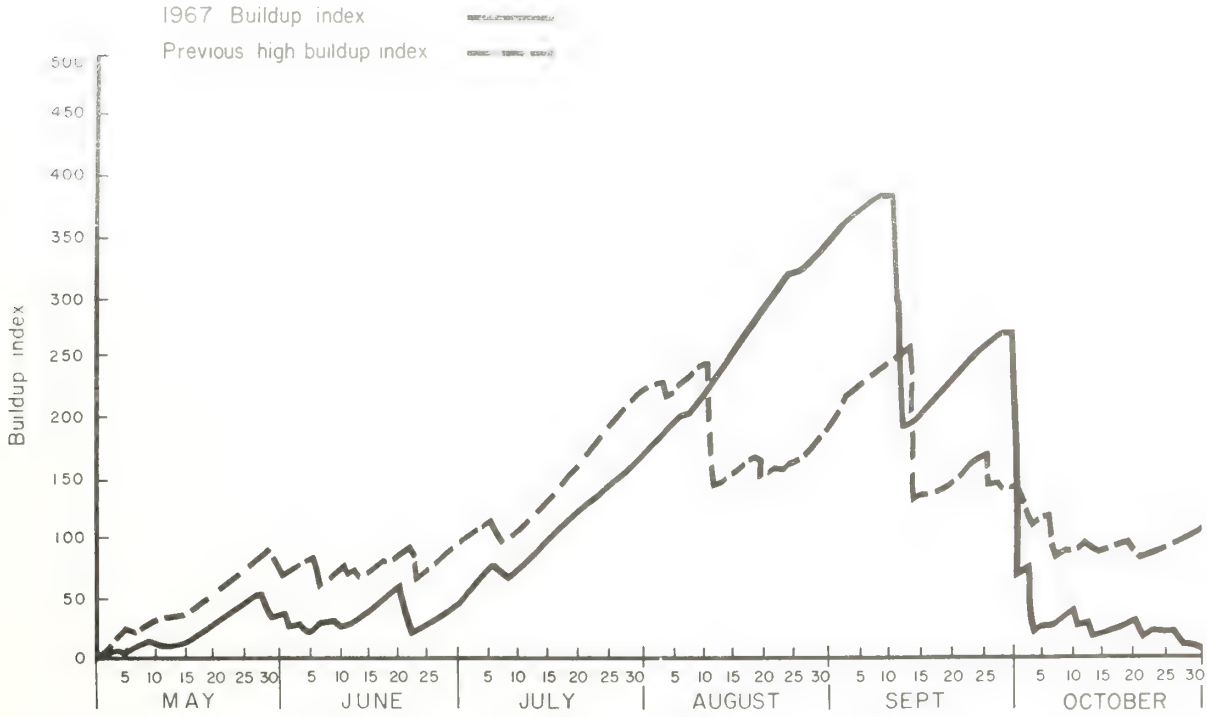


Figure 3. – Buildup index for 1967 compared with previous record high for period of 1954-1966.

was issued for northern Idaho to expect increasing southwest winds 18-25 m.p.h. on September 1. These winds did increase steadily during the morning of September 1 and continued until late that evening.

THE EARLY DAYS – August 11 to 31

This, then, was the weather picture. For the fire activity preceding the major run on September 1, we have information from the Priest Lake Timber Protective Association and the Division of Fire Control, Northern Region, U. S. Forest Service. On August 11, a lightning storm moved over the area causing five fires on or near Sundance Mountain. Three of the fires were discovered and attacked on the 11th, and two were declared out that same day; the third was declared out on August 15. A fourth fire was discovered on August 20, and 37 men, including 12 smokejumpers, brought the fire under control that evening — 1830 — with 2 acres burned. The fire was declared out on August 25 but was monitored by air patrol for several days.

At 2240 on August 23, fire number 5 broke out near the Sundance Lookout. The fire was contained by the end of the day, August 24, with an estimated 35 acres burned. Suppression activities continued for the next 5 days. Late in the evening of August 29, at 2220, Priest Lake Timber Protective Association Headquarters near Coolin, Idaho, received word the fire had jumped the line and was out of control. Men and equipment were evacuated to headquarters. The fire was observed rolling down the hill in the Lee Creek drainage. A northeast wind had prevailed throughout the day and it is assumed this wind, coupled with the normal nighttime downslope currents, resulted in a wind-driven fire moving downslope. Information available from observers indicated the winds were

Figure 4. – Looking west at Sundance Mountain after the fire's night run toward Coolin on August 29. Lost Creek in foreground; Soldier Creek on right.

20-25 m.p.h. on the fire, but there was calm at Cavanaugh Bay near Coolin. The ground and crown fires were observed to move as a single front, with spotting up to one-half mile ahead. The main advance took place between 2230, August 29, and 0200, August 30, which would give an average rate of spread of 0.80 m.p.h.

At 0700, August 30, the total acreage burned was reported as over 2,000 acres. Very little enlargement of fire area occurred, and there were only a few minor runs in the afternoon. Both Soldier Creek and Lost Creek drainages were now threatened if the wind shifted to the southwest (fig. 4). On August 31, heavy smoke obscured the fire most of the day, but a spot fire broke out across a dozer line about 1700 and resulted in an intense burnout of lower Lost Creek. The southwest winds were starting to exert some influence judging by ash fallout reported by residents near Naples, Idaho, 18 miles to the northeast. Eight bulldozers were opening roads in the McCormick and Jeru Creek drainages.

From this point, the story is best told in hourly reports of fire progress, which can be followed on the foldout map showing the fire-edge lines. The hourly progress of the fire was determined from the eyewitness accounts obtained through interviews. The approximate time an individual was in an area and where he saw the fire or the fire front were synchronized with the other observations. From this consolidated information, a coherent description of the fire's rate of spread was developed.

THE MAJOR RUN — September 1, 1967

0700. The fire area had enlarged to approximately 4,000 acres and the eastern fire edge extended from the ridge between East River and Lost Creek north around Sundance Mountain and down into Soldier Creek (see foldout map). At 1010 on September 1, the U. S. D. A. Forest Service was requested to take over fire suppression activities on the Sundance Fire.

Up to 1300. Fire activity had not increased significantly as reported by the air patrol observer, who had flown close to the perimeter. A run along the ridge between East River and Lost Creek had occurred since 0700 but was not burning intensely.

1400. The fire had started its advance to the northeast (see foldout map), the initial activity being in Lost Creek, which is at a higher elevation than Soldier Creek. In Soldier Creek the fire moved in a northeasterly direction along contours and downslope from Sundance Mountain. At this time the fire was considered to be a ground fire, consuming most of the brush and some crown material.

Bulldozers were continuing to open roads east of the Selkirk Divide. Action was started to pull the equipment back. A fire camp had been established in Pack River south of Jeru Creek near Lindsey Creek.

1500. By now the fire had increased in intensity, crossed Soldier Creek to the northeast side, continued up the south side, and reached the ridgetop in Lost Creek southwest of Jeru Peak. The fire was spotting across the Divide south of Jeru Peak and coming back up the east exposure slopes. The main front was becoming more brush and crown fire, with the brush controlling spread.

1600. Lost Creek had burned out and spreading had been stalled by the Divide. The fires burning upslope on the east side were influenced by indraft winds. In Soldier Creek the entire front had become a crowning fire. Winds were carrying firebrands across the Divide and spot fires were burning upslope. Fire-induced winds were approaching 80 m.p.h., resulting in some timber blowdown. The ground fire was lagging the main front and the brush was providing continuity to sustain the crowning fire.

Dozers working at the head of Jeru Creek prepared to move back to Pack River. At about 1600, a two-man rescue team left Pack River fire camp by pickup truck to bring out men working the head of McCormick Creek.

1700. The Selkirk Divide slowed the fire front; however, firebrands were being cast to the northeast. The ground fire moved up to

Figure 5. – Convection column above Sundance Fire looking east, at 1700 on September 1, 1967.

Figure 6. – Fire destruction at mouth of McCormick Creek. Logging area on right.

the Divide, meeting the spot fires burning up the east slopes between Jeru Peak and Hunt Peak. The convection column (fig. 5) reached a height of 25,000 ft. at this time and was detected as a weak echo by the U. S. Weather Bureau radar at Missoula, Montana.

The rescue team had entered McCormick Creek and reported the smoke column was 4 to 6 miles wide. The dozers had moved out of the heads of Jeru and Hellroaring Creeks.

1800. During this period the fire intensity decreased as the small fuel sizes were consumed. The spot fires on the east portion of the fire front, being influenced by the prevailing wind, became consolidated and quickly developed into a crowning fire. The large advancement of the fire between 1700 and 1800 may be seen on the foldout map.

The rescue team paced the fire while returning to Pack River after being blocked by the fire in McCormick Creek. As the rescue team reached the mouth of McCormick Creek (fig. 6), they could see flames on the ridge just southwest of them. The Roman Nose lookout could not see any fire because of the

Figure 7. – Blowdown and burnout in Pack River area.

smoke pall. A scout had left the Pack River camp and was at Youngs Creek trying to establish radio contact with the rescue team. Sometime during this period, the fire overran the dozer boss and operator near Fault Lake at the head of McCormick Creek. As the rescue team reached the mouth of McCormick Creek (fig. 6), they could see flames on the ridge just southwest of them.

1900. As the fire front reached the lower reaches of the ridge between McCormick and Homestead Creeks, it was slowed by the steeper slopes, indrafts coming up and down Pack River, and a suppressed wind effect at the lower elevations. The ground fire was probably lagging the main front with the brush controlling spread, but considerable crowning was still occurring.

The rescue team moved down Pack River under the advancing front of the fire and met the scout at Youngs Creek. Winds were breaking boughs and tops out of nearby young timber. Considerable spotting over Pack River was observed by others but the rescue team and scout saw only one large firebrand. While at Youngs Creek they saw fire cross the road about one-fourth mile upriver. They moved out toward the fire camp and estimated they were 3 to 4 minutes ahead of the fire. Upon their return to the fire camp, radio contact was made with the Roman Nose lookout instructing him to meet a pickup truck in Falls Creek. The pickup left Sandpoint, Idaho, near 1900.

2000. Shortly after 1900 the fire swept down Jeru Creek so that the entire 5-mile front was in the Pack River drainage (see fold-out map). For the next half hour the fire front was nearly stalled due to the turbulent winds created by indrafts up and down Pack River and down McCormick Creek. Fire whirls were triggered by these winds and moved randomly in the area near the Pack River bridge and the junction of McCormick Creek and Pack River. The indrafts and fire whirls caused extensive blowdown and tree breakage, as may be seen in figures 7 and 8. The fire activity in this area must have been similar to the classical "fire storm" with its intense burnout and associated winds in a fixed area.

Figure 8. – Valley fire storm area.

The Roman Nose lookout had left the area to meet the pickup in Falls Creek. At 1930 he encountered a large spot fire blocking any further advance toward Falls Creek and turned back to the lookout. About 20 minutes later at 1950 the entire west slope of Apache Ridge appeared to ignite simultaneously. Observers at the Pack River fire camp stated no flame was visible one minute and the next the whole slope was aflame. The turbulent winds, convective and radiant preheating, and the firebrands lofted by the whirls evidently contributed to the ignition process. The fire swiftly moved up the slope and developed into a crowning fire. Rate of spread accelerated as the fire approached the ridgeline and firebrands were cast far in advance of the front. The convection column reached an altitude of 31,000 ft. at 2000 (fig. 9).

The pickup sent for the Roman Nose lookout entered Falls Creek about 1930 and was buffeted by extremely strong winds and dust devils as he headed for the Roman Nose Creek crossing. The dust devils occurred rather regularly and were estimated to be between 10 and 25 ft. in diameter.

2100. After sweeping over Apache Ridge and moving into Falls and Roman Nose drainages, the fire slowed. It was still a crowning fire, sometimes with flames moving horizontally through the crowns. Between about 2015 and 2100, the lookout observed spot fires far ahead of the front in Falls Creek; large spot fires were also seen above Roman Nose Lake No. 1. Meanwhile the pickup had reached Roman Nose Creek crossing. The driver saw fire to the west and southwest moving toward him. Upon turning around and leaving the area, he saw firebrands and large embers flying horizontally.

At 2025, a spot fire started at the mouth of Snow Creek and at 2045 another started in Myrtle Creek (see foldout map). These spot fires were at least 10 miles in advance of the main front. In addition, numerous firebrands were falling to the ground at the intermediate distances. The spot fires observed from Black Mountain burned as both heading and backing fires, and one was observed to spread suddenly in all directions, developing a radial pattern of fire spread. At the same time, the convection column rose to 35,000 ft. and the pilot observer felt it was continuing to build. Long-range firebrands were being transported by at least two possible mechanisms:

1. By being carried aloft in the convection column, then entering the influence of the

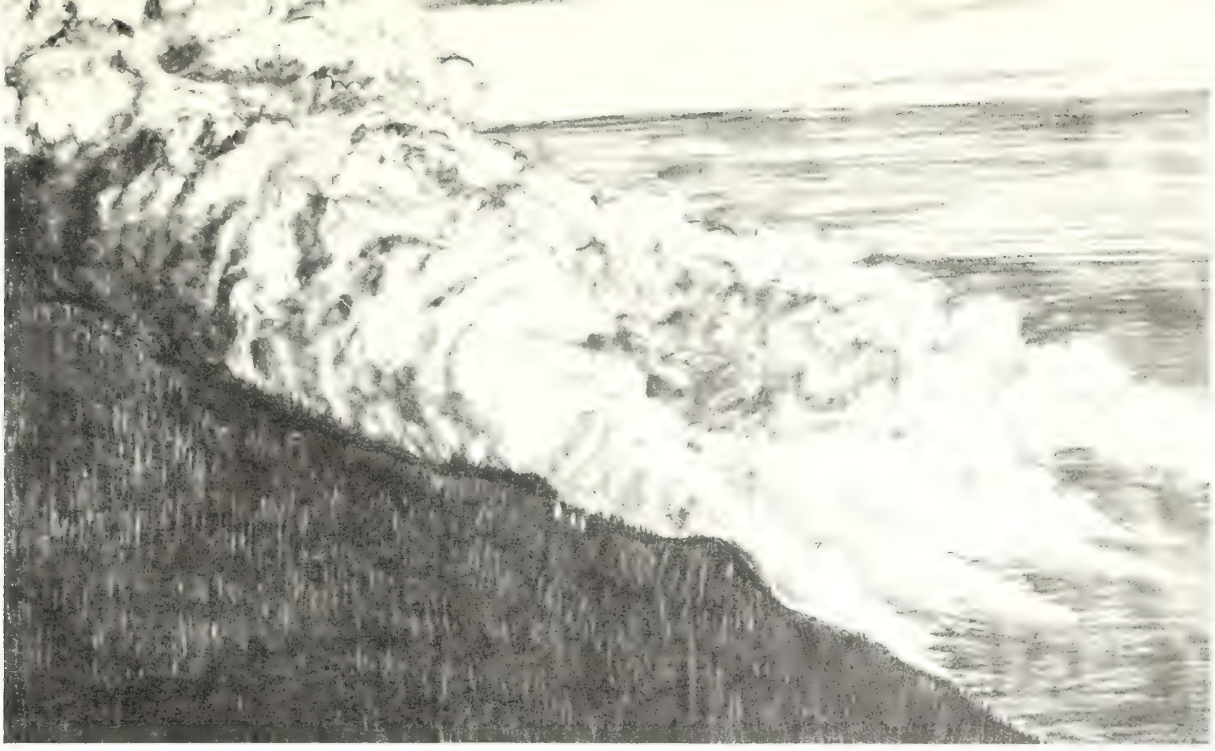


Figure 9. – Artist's conception of convection column, then about 31,000 ft. high, made from slide taken by jet pilot over fire near 2 000 hours.

prevailing wind and falling under the gravitational influence (8)[1] ;

2. By being carried aloft in the convection column, then entering the influence of a vortex street and being stabilized in it. The vortex street moved on downstream of the strong convection column (1). (For a more detailed discussion of this point, see the section below titled "Firebrand Activity.")

As the man on Roman Nose Lookout retreated to a rockslide, where he stayed until the fire had abated the following day, a crowning fire moved up Zuni Creek out of Pack River and carried over into Ruby Creek.

2200. By this time the fire had moved from Ruby Ridge into Ruby Creek and additional spotting occurred on Caribou Ridge (see foldout map). The fire front had become broken, probably for several reasons, including the facts that more area had been logged over a long period of time, so little slash was present, and that the spot fires had not consolidated into a single front. Hence there was poor fuel continuity and the main fire front was deprived of fuel. Sporadic flareups were occurring, indicating the meeting of heading and backing fires or burnout of pockets of fuel. At this time the fire was primarily a brush fire, with considerable crowning.

2300 on into September 2, 1967. The fire became more affected by prior burnout and became a ground fire as it moved into Caribou Creek. The rate of spread had decreased although some crowning took place. The main front had become poorly defined because of reduced fuel continuity. Nearly 60 percent of the area could now be considered affected by previous burning.

A spot fire northeast of the main fire zone was reported at 2345. This probably resulted from the spot fire at the mouth of Snow Creek. Various portions of the fire became individual fires that resulted in flank increases and an occasional minor run. This type of behavior continued until the fire was controlled.

Weather conditions continued to improve during the night (see table 2, p. 16). Observations made in Ruby, Highland, and Falls Creeks at 0200 indicated the fire was cooling down.

One of the greatest concerns at this time was the possibility of a wind shift to the northwest or southeast. A fire front 20 miles wide would have resulted; however, the wind held steady and the acreage increased only slightly, 4 percent, before control was achieved.

[1] *Numbers in parentheses refer to Literature Cited.*

THE FIRE PHENOMENA

From the fire story told in the preceding section, it is clear that a great deal was happening in a short time on the Sundance Fire. The investigating team has analyzed the fire records to determine conditions such as weather, rate of spread, fuel loading and consumption, and fire intensity. For purposes of comparison, some of these determinations will be presented as an hourly log of the fire's major run.

WEATHER

A detailed analysis of the atmospheric conditions leading up to the fire and through 12 hours after its run was made by the meteorological personnel of the Fire Laboratory. Estimated hourly free-atmosphere conditions — wind, temperature, and humidity — both preceding and during the major run of the fire, were derived for 5,000 ft. m.s.l. (Free-atmosphere conditions are those which would be experienced at some height above the ground, removed from surface influences.)

The account that has been given of the progress of the fire has emphasized the importance of the weather influences and has included a description of the weather preceding the major outbreak of the fire. An illustrated analysis of the general weather pattern associated with the fire is given in Appendix 2. Bihourly reports on weather conditions during the major run are given in the log.

With regard to temperature, it should be noted that the quantity of heat released by the fire modified the reported temperatures considerably near the ground, as evidenced by small islands of desiccated foliage. On the other hand, the general winds on the fire were probably always lower than those calculated for free-atmosphere conditions except where accelerated by fire-induced forces.

RATE OF SPREAD

It is evident from the fire story given earlier that the Sundance Fire spread with unusual rapidity during certain periods, slowing somewhat in the intervals. In the Log (p. 13), calculations for rate of spread are given for each hour. These are average values corresponding to the time and distance interval shown on the foldout map.

It is interesting that the fire-spread indices based on the National Fire-Danger Rating System, averaged for the stations in the area, predicted actual conditions quite well. This is evident from the following comparison:

	Predicted (0800)	Actual (1600)
August 31	30	36
September 1	52	64
September 2	60	52

FUEL LOADING AND CONSUMPTION

The forest burned by the Sundance Fire was composed of mixed conifer stands interspersed with logged areas (fig. 10). A variety of stand conditions ranging from young to overmature and poorly to heavily stocked existed before the burn.

To determine fuel loading, measurements were made on nearby areas comparable to those burned, as well as on the burned area itself. The fuel complex was considered to contain three levels: ground litter, brush, and crown material.

Timber inventories for the Kaniksu Working Circle were used to estimate the crown fuel weight, by a method based on research done by Fahnestock (3). Data from the State of Idaho indicated that timber distribution on private and public lands should be similar, so the timber estimates based on Forest Service records were applied to the whole fire area. The average crown fuel load was estimated at 2.04 tons per acre. Field measurements yielded a value of 5.25 tons per acre in a heavily stocked stand.

The brush level was estimated by field sampling at a loading of 2.7 tons per acre. Visual observations throughout the burn area indicated the brush loading could have varied from 1 to 20 tons per acre, but the estimated average should be reasonable.

Figure 10. – Clearcut logging area (left foreground) at the site of the Sundance Fire. At this time, on August 30, the fire was backing into Soldier Creek drainage.

Ground litter loadings were obtained from field sampling and found to be near 20 tons per acre. Again, in some areas the loadings could have been as low as 1 ton per acre.

In determinations of fuel loading, crown material was limited to foliage and branches under 1/8-inch diameter, since field inspection of residual stems indicated most of such material was consumed. Areas where larger material in the crowns was burned were evident, but were disregarded in the computations. The maximum size for brush material was set at one-fourth inch, based on field sampling.

Ground litter loadings varied considerably, but the field-obtained values were accepted as representative. The effects of logging slash and its treatment on the fire's intensity are difficult to evaluate. About 50 percent of the untreated logging slash in the area was more than 8 years old. Most of the fresh slash was at the southwest end of the fire area and was burned the day before the major run. Slash areas, therefore, were not considered to be different from the timbered areas in ground-litter determinations.

Details of the calculations of fuel loading are given in Appendix 1, along with a description of the measurements of moisture content. Samples of the fuels were taken to establish moisture content levels in each stratum.

Percentage estimates of fuel consumption are given in the Log, at approximately hourly intervals. These percentages are based on information gathered during the interviews, research data, and the acquired knowledge of experienced firefighters. The amount of fuel from each of the three fuel levels consumed in the fire front was estimated after considering the terrain and wind conditions, the rate of spread, and the observations of eyewitnesses. For example, where the fire front is being carried by the brush level at a low rate of spread with little wind we might consider that 90-percent available ground +95-percent brush +20-percent crown fuel

was being consumed in the fire front. The percentages apply to the size classes and loading as previously described.

Laboratory work (7) has shown that the percent of ground fuel burned in the flame front decreases as windspeed increases. We estimated 20-percent ground fuel consumption in our calculations. The difference between this and the field-determined amount consumed is assumed to have been burned by sporadic flaming and glowing combustion following passage of the main fire front.

INTENSITY

Fire intensity values were calculated and are given in the Log at hourly intervals, along with values for maximum energy release from the total front. These, too, are average values corresponding to the time and distance intervals.

As explained earlier, physical constants for loading and moisture content of strata were derived. These constants established the amount of fuel on the site that could contribute energy to the fire. The average energy content of fuel was set at 8,500 B.t.u./lb.; the heat required to remove the moisture and raise the fuel to ignition in each fuel level was then subtracted to arrive at an energy release potential (B.t.u./lb.). Values of the energy potential per unit were calculated by multiplying the loading, corrected to pounds per square foot, by the energy release potential. For any time interval of interest, the energy per unit area was combined with the percent consumption values to obtain the energy released per unit area. Fire intensity and total energy release rate were calculated by use of the rate-of-spread determinations and application of laboratory findings for residence time (time the flaming zone exists at one point).[2] The physical constants for the three fuel levels are given in table 1.

The values for energy release rate are shown in figure 11, for a 12-hour period that includes the fire's major run. To arrive at our values, the residence time for the fire-controlling fuel level was combined with a rate of spread to establish a flame depth. The active combustion area was calculated by multiplying the fire edge length by the flame depth. The combination of the combustion area and the energy released per unit area divided by the residence time yielded the total energy release rate per unit time (B.t.u./sec.).

Fire intensity in B.t.u. per second per foot of fireline (fire edge) was calculated after Byram (2, chap. 3, p.79). Values were obtained by combining the summed energy per unit area and the rate of spread for a time interval. The fire intensity values (fig. 12) appear reasonable when compared with the limits established by Byram. He gives an

[2] *Anderson, Hal E. Heat transfer and fire spread. U.S.D.A. Forest Serv., Intermountain Forest and Range Exp. Sta., Ogden, Utah. (In preparation.)*

Table 1. – Estimated fuel constants for the Sundance Fire area.

Fuel strata	Loading		Moisture content	Residence time	Energy release potential[1]	Energy per unit area
	Ton/acre		Percent	Min.	B.t.u./lb.	B.t.u./sq.ft.
Ground litter	20	(max.)	12	1.0	7,675	7,060
	1	(min.)	12	1.0	7,675	384
Brush	2.7	(ave.)	60	2.0	7,718	957
Crown	5.25	(max.)	145	0.33	6,773	1,630
	2.04	(min.)	145	0.33	6,773	636

[1] *Corrected for moisture and heat to ignition.*

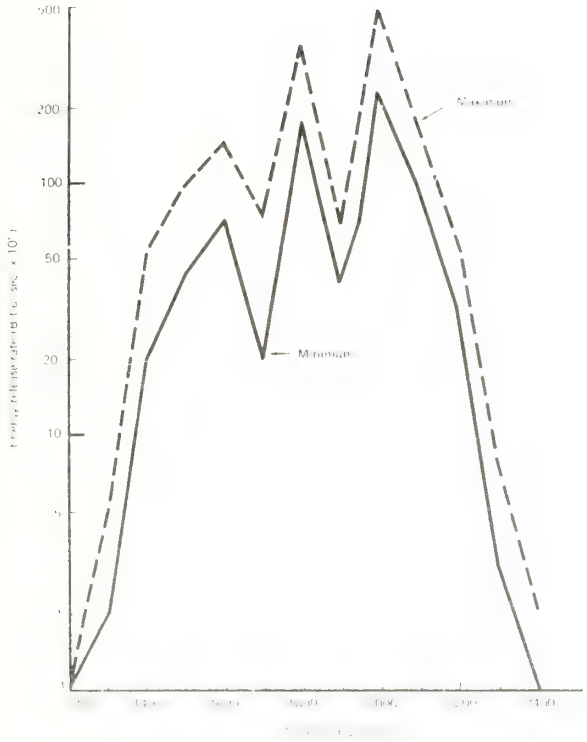


Figure 11. – Rate of energy release at fire front over a 12-hour period on September 1.

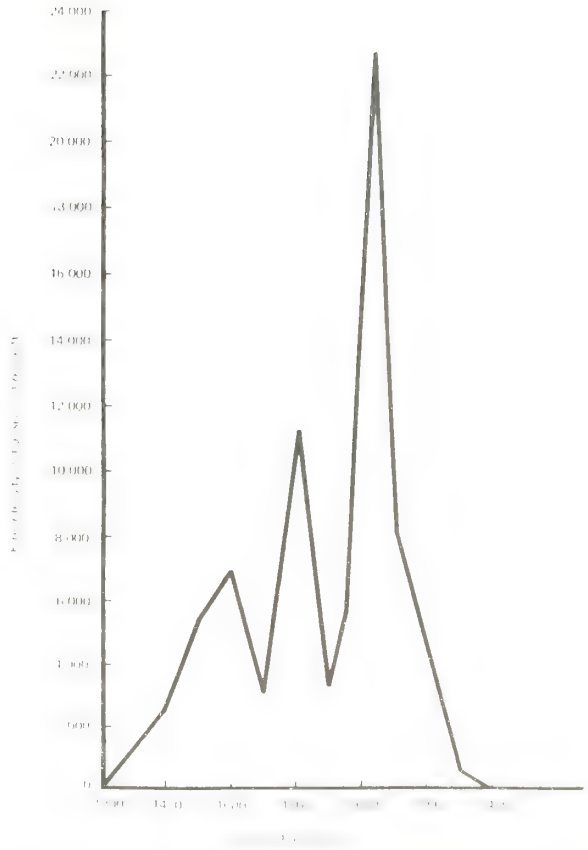


Figure 12. – Fire intensity calculated by Byram's method for a 12-hour period on September 1.

upper limit of 30,000 B.t.u./sec.-ft. for large wildfires, whereas we derived a value of 22,500 B.t.u./sec.-ft. for the Sundance Fire.

The values given here are only approximations, since the derived residence time is an estimate. Each level of fuel and each size of fuel has its own residence time, which may or may not overlap that of the next size. This means residence time may be underestimated because of the sequential ignition and burnout of fuel sizes in increasing order. This probability seems partially verified by the nature of the flame-depth values, which were determined using the assigned residence time and the deduced rate of spread. Flame depth varied from a minimum of 44.0 ft. to a maximum of 264.0 ft., a range that appears narrow for the existing conditions.

FIRE LOG FOR SEPTEMBER 1

0700. Fire area 4,000 acres; fire edge extends from ridge between East River and Lost Creek north around Sundance Mountain and down into Soldier Creek.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 14 m.p.h. SW; relative humidity 25 percent; dry-bulb temperature 71° F.

Up to 1300. No significant increase in fire area. Increased activity in Lost Creek showed the fire front was becoming more active. Weak convec-

tion column over burned area meant an increase in windspeed could have a prompt influence on rate of fire spread at the boundaries.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 20 m.p.h. SW; relative humidity 27 percent; dry-bulb temperature 77° F.

1400. Fire advancing to northeast; mainly ground fire.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 21 m.p.h. SW; relative humidity 25 percent; dry-bulb temperature 78° F.

Rate of spread. 0.75 m.p.h.

Fuels. Main fire front: 20-percent ground +75-percent brush +10-percent crown.

Intensity. Maximum energy release rate from total front: 53 X 10^6 B.t.u./sec.; fire intensity: 1,000 B.t.u./sec.-ft.

1500. Fire has advanced to ridge southwest of Jeru Peak; main front brush and crown fire.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 24 m.p.h. SW; relative humidity 22 percent; dry-bulb temperature 78° F.

Rate of spread. 1.25 m.p.h.

Fuels. Main fire front: 20-percent ground +90-percent brush +40-percent crown.

Intensity. Maximum energy release rate: 100 X 10^6 B.t.u./sec.; fire intensity: 5,400 B.t.u./sec.-ft.

1600. Fire at Selkirk Divide; ground fire lagging main front, brush sustaining crowning fire.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 25 m.p.h. SW; relative humidity 20 percent; dry-bulb temperature near 77° F.

Rate of spread. 1.6 m.p.h.

Fuels. Main front: 10-percent ground +95-percent brush +80-percent crown.

Intensity. Maximum energy release rate: 145 X 10^6 B.t.u./sec.; fire intensity: 6,900 B.t.u./sec.-ft.

1700. Fire moving slowly across Divide; convection column 25,000 ft. high.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 29 m.p.h. SW; relative humidity 20 percent; dry-bulb temperature 75° F.

Rate of spread. Less than 1 m.p.h.

Fuels. Main fire front: 30-percent ground +85-percent brush +20-percent crown.

Intensity. Maximum energy release rate: 73 X 10^6 B.t.u./sec.; fire intensity: 3,150 B.t.u./sec.-ft.

1800. Fire has advanced on east front.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 33 m.p.h.; relative humidity 20 percent; dry-bulb temperature 73° F.

Rate of spread. 2.5 m.p.h.; could have peaked at more than 5 to 8 m.p.h., as measured by rescue team.

Fuels. In frontal advance: 10-percent ground +90-percent brush +95-percent crown.

Intensity. Maximum energy release rate: 358 X 10^6 B.t.u./sec.; fire intensity: 11,300 B.t.u./sec.-ft. — highest level up to this time.

1900. Fire has reached ridge between McCormick and Homestead Creeks; ground fire lagging main front, brush controlling spread, considerable crowning.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 37 m.p.h. SW; relative humidity 21 percent; dry-bulb temperature 71° F.

Rate of spread. 1 m.p.h.

Fuels. In frontal advance: 6-percent ground +95-percent brush +60-percent crown.

Intensity. Maximum energy release rate: 72 X 10^6 B.t.u./sec.; fire intensity: 3,400 B.t.u./sec.-ft.

2000. Fire in Pack River drainage; "fire storm"; convection column 31,000 ft.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 44 m.p.h. SW; relative humidity 23 percent; dry-bulb temperature 68° F.

Rate of spread. 6 m.p.h. approaching Apache Ridge.

Fuels. In frontal advance: 6-percent ground +60-percent brush +95-percent crown.

Intensity. Maximum energy release rate: 474 X 10^6 B.t.u./sec.; fire intensity: 22,500 B.t.u./sec.-ft. These are maximum values for the entire run.

2100. Fire has advanced over Apache Ridge and into Falls and Roman Nose drainages; convection column 35,000 ft.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 45 m.p.h. SW; relative humidity 28 percent; dry-bulb temperature 66° F. Windspeed as checked by Roman Nose lookout was steady at 35 to 40 m.p.h.

Rate of spread. 2.5 m.p.h.

Fuels. In fire front: 4-percent ground +70-percent brush +80-percent crown.

Intensity. Maximum energy release rate: 174 X 10^6 B.t.u./sec.; fire intensity: 8,250 B.t.u./sec.-ft.

2200. Fire at Ruby Ridge and Ruby Creek; spotting on Caribou Ridge; broken front; brush fire with considerable crowning.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 52 m.p.h. SW; relative humidity 31 percent; dry-bulb temperature 65° F.

Rate of spread. 1.5 m.p.h.

Fuels. Approximately 30 percent of fuel previously affected by spot fires; fuel available to front: 6-percent ground +80-percent brush +70-percent crown.

Intensity. Maximum energy release rate: 60 X 10^6 B.t.u./sec.; fire intensity: 3,800 B.t.u./sec.-ft.

2300 and on into September 2. Fire moving into Caribou Creek; main front poorly defined; fire cooling down.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 49 m.p.h. SW; relative humidity 36 percent; dry-bulb temperature 63° F. With the winds decreasing and the relative humidity increasing, general conditions on the fire were improving as shown in table 2. Winds on the fire were about 10 m.p.h. in Ruby, Highland, and Falls Creeks at 0200.

Rate of spread. 0.5 m.p.h. or less.

Fuels. In fire front: 6-percent ground +60-percent brush +50-percent crown.

Intensity. Maximum energy release rate: 7.8 X 10^6 B.t.u./sec.; fire intensity: 735 B.t.u./sec.-ft.

Table 2. — Estimates of free-atmosphere conditions from 2200, September 1, 1967, to 0600, September 2, 1967.

Time	Wind (SW)	Relative humidity	Dry-bulb temperature
	M.p.h.	Percent	°F.
2200	52	31	65
2400	48	41	61
0200	39	50	58
0400	31	62	54
0600	25	71	52

SOME PROMINENT FIRE FEATURES

The run of the Sundance Fire and its end cannot be attributed to any single factor. The wide front, dry fuels, and winds certainly played major roles in its advance, but firebrand activity was also instrumental. The termination of the run was influenced by the decrease in windspeed and the increase in humidity, and again by the firebrand activity that caused burned-out areas ahead of the main front. In addition the terrain was sloping downhill and prior logging activities had removed part of the fuel continuity. Like any fire, this one was controlled by nature's infinite variety of conditions and their combinations. The best we can do is assess the influence of the obvious variables, estimate their relative importance, and attempt to describe how the fire probably responded to each.

To some extent, this has been done in the preceding pages. However, some additional comments may be helpful with respect to certain outstanding features of the fire.

INFLUENCE OF TERRAIN AND WIND ON FIRE SPREAD

The rate of spread of this fire was strongly influenced by the terrain features and the wind, singly or in combination. If figure 13, showing the changes in rate of spread during the major run, is correlated with the topographic diagram (fig. 1), the windspeeds reported in the Log, and the foldout map, the influence of terrain and wind may be clearly seen.

In Soldier Creek the rate of fire-front advance can be attributed to the slope and wind. The upslope terrain, exposed to southwest airflow from across a broad valley, allowed a crowning fire to become established at a lower windspeed. The fire probably accelerated until it reached the Selkirk Divide where it was slowed by backing fire from the spot fires and its own induced winds.

Down into Pack River along McCormick Creek and Homestead Creek the wind was strong enough to push a crowning fire downslope. However, at the lower elevations the winds had less effect, the slopes became more steep, and indrafts countered the surface wind so the fire moved at a slower rate.

The sharp increase in rate of spread over Apache Ridge can be attributed to preheating of fuel, spotting, upslope, and movement of the front into the wind's influence. Massive spotting and high winds advanced the fire through Falls Creek. The fire moved on to lower elevations where the winds were not so effective and in some areas backing spot fires developed a firebreak that slowed the spread.

In addition the relative humidity rose above 30 percent toward the end of the run and may have prevented some spotting activity. Experience indicates that spotting tends to diminish when relative humidities rise above 30 percent.

BLOWDOWN

The extent of timber blowdown prompted an investigation of the probable indraft maximum in selected areas. Work carried out by Lommasson (5) on mass fires or fire storms

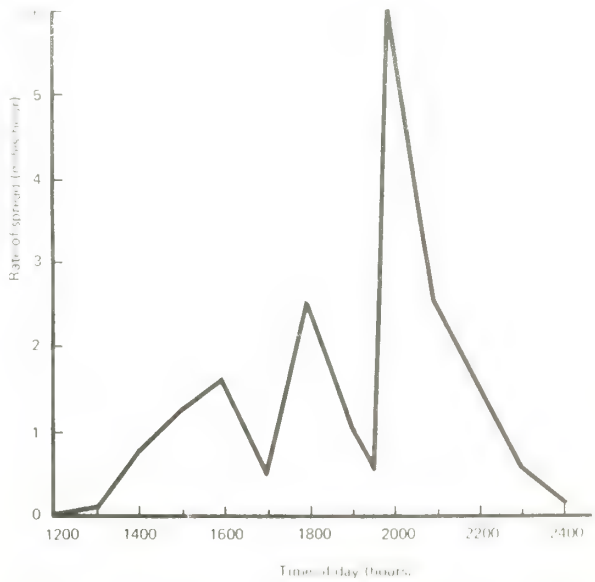


Figure 13. – Rate of fire spread during a 12-hour period on September 1.

Figure 14. – Blowdown in Falls Creek area.

has provided a means of estimating indraft winds. His equation also provided the means of determining whether our values for flame depth and energy release were reasonable or not. The equation is

$$V_w = \frac{(88 \times 10^{-3}) \left(\frac{dE_T}{dt}\right)^{1/3}}{\sqrt[6]{A}}$$

where

V_w = windspeed, m.p.h.

$\frac{dE_T}{dt}$ = total energy release rate, B.t.u./sec.

A = combustion area, sq. miles.

Values for four areas where blowdown was evident in aerial photographs (fig. 14) were tested with this equation:

Up Soldier Creek	V_w = 80 m.p.h.
Down Upper McCormick Creek	V_w = 95 m.p.h.
Over Apache Ridge	V_w = 96 m.p.h.
Across Falls Creek	V_w = 80 m.p.h.

It has been generally estimated that winds in excess of 80 m.p.h. are needed to cause blowdown. Owen Cramer of the U. S. D. A. Forest Service, Pacific Northwest Station, after viewing slides of the damage, informally estimated the winds to be near 120 m.p.h. The agreement of our values with other estimates, considering the extrapolations we used, encourages continued efforts to develop theories and mathematical descriptions of field-observed phenomena.

FIREBRAND ACTIVITY

Firebrands and spotting were evident throughout the fire run and are believed to have played an important role in the fire's behavior. From the pattern of rate of spread and the record of reported fires, it was apparent that firebrand material had been carried 10 to 12 miles in advance of the main fire front. Much debris was found northeast of the fire area (fig. 15) in the form of moss and lichen strands or wreaths, larch and hemlock cones, needles, cedar fronds, branches the size of a pencil, and pieces of bark up to 4½ inches long and 1½ inches wide. The fallout

FALL OUT FOUND AT
BONNERS FERRY AIRPORT
9/1/67

Figure 15. – Debris and possible firebrand material found at Bonners Ferry airport, September 1, 1967.

of this debris was widespread over the area northeast of the fire. Much of it was scorched or blackened but the particles had not burned to completion. Neither had they successfully ignited their surroundings. Reports of burning material falling near residences in the Kootenai Valley were received but none of this material was positively identified as burning when it landed.

What kind, size, and shape of burning material could most likely have been carried such distances? Work done in Spain by Tarifa (8) was examined. He investigated the flight paths of spheres, cylinders, and rectangular plates and their burning characteristics to determine the lifetime of firebrands and the probable range. Various species of wood were used and some study was made of pine cones and charcoal elements.

In studying his results, we found that wood elements would have to be large and carried quite high in the convection column to have a 10-mile range. The burning process, according to Tarifa, is glowing combustion, not flaming. Flaming firebrands existed only at low windspeeds. Charcoal brands have much longer burning times than any of the woods or natural firebrands. Pine cones burn much like wood once the scales have burned off.

For our study we had an estimate of the wind and the distance the brands had to travel. We calculated the drag coefficient, terminal velocity, and mean velocity of fall for four types of brands: (a) a charcoal sphere, 1 inch in diameter; (b) a charcoal cylinder, 1.75 inches long and 0.6 inch in diameter; (c) a flat charcoal plate, 1.1 inches square and 0.43 inch thick; and (d) a pine cone about 3.75 inches long and 2.2 inches in diameter. We used the techniques presented by Tarifa to calculate the maximum flight time possible for each brand. This we considered as the time the brand would remain burning; thus the particle would have to reach the ground within this time period to ignite other material. From the mean velocity of fall and time of flight, we could calculate the height at which a particle of the given size must be cast — that is, the ejection altitude. In turn, we could then calculate the vertical velocity in the convection column required to carry

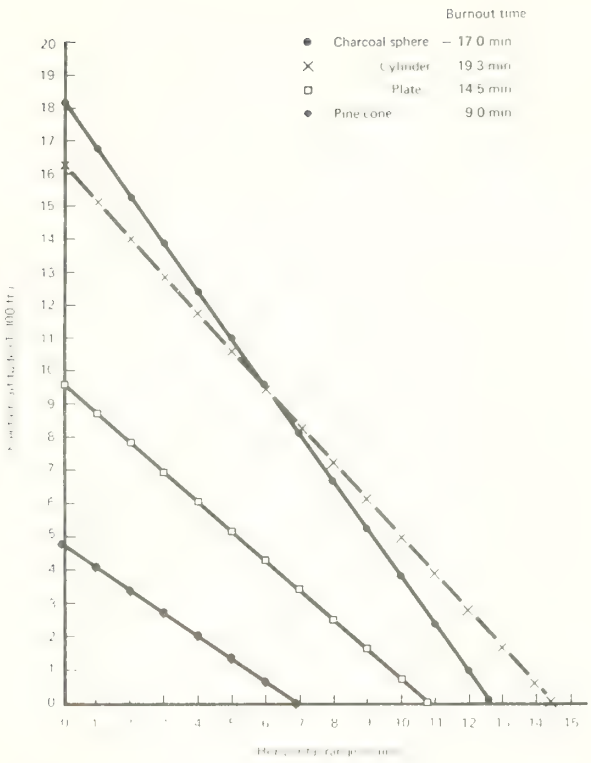


Figure 16. – Range of various types of firebrand material.

the brand to the proper height. The results of these calculations are shown in figure 16.

Any of the charcoal brands could have traveled the 10 to 12 miles in a glowing state, whereas the pine cone could have transported fire up to 7 miles. With a convection column developing to over 31,000 feet, it appears reasonable that vertical velocities of 45 m.p.h. would have existed and material could have been carried to altitudes over 18,000 feet in the convection column. Winds of 44 m.p.h. or greater did exist and could have carried the brand once it tumbled out of the column.

This method of firebrand transport appears quite reasonable but other possibilities do exist. Currently under investigation is the possibility that moving vortices are generated by the fire and prevailing wind. The swirling air or vortices would move on downstream carrying firebrands and debris with them. The intensity and range of these vortices would depend on the amount of heat "pumped" into them by the fire and strength of the wind. Particles carried aloft would tend to either stabilize within the vortex or centrifuge out. Particles with low drag configurations (fig. 15) would tend to stabilize, and as the vortex street dissipated far downstream of the convection column, the suspended debris would "touch down" (1).

Several behavior characteristics noted by the people interviewed support this possibility. It has been stated earlier that the pickup man for the Roman Nose lookout encountered very intense winds and what he described as "dust devils" in Falls Creek ahead of the fire. The occurrence of these dust devils was periodic. The same man encountered similar winds later in the Snow Creek area. The lookout on Black Mountain observed a spot fire which fanned out in all directions in a circular manner. The tree-fall pattern in Falls Creek suggests the trees fell toward the centerline of the fire path from each side. These pieces of evidence have encouraged the investigation of the potential effectiveness of this phenomena (1).

FIRE ACTIVITIES IN PACK RIVER

The Pack River area has received the greatest attention by the news media because of its accessibility, the obvious destructive forces associated with the fire, and the dramatic burning of the Pack River bridge. This area was surveyed by the research team in an attempt to localize the forces the fire exerted; however, these forces appear to have been so dynamic and fluctuating that the evidence remaining is not coherent.

Shortly before the fire entered this area we know men near the river felt very little wind but could hear it overhead. Yet trees that had toppled into the river had green unscorched boughs underwater and burned limbs above water. This indicated that strong winds were present in the valley bottom very shortly before the fire arrived, or before the fire ignited the crown material. Some downed trees showed no signs of burning on the underside, although the upper side was charred.

Winds of different magnitudes and directions may be inferred from the pattern of blowdown and breakage. The tops of many trees were snapped out either by a sudden sharp rush of air or from whipping back and

forth, while a great many trees fell under the force of a strong, sustained high wind. The trees with snapped tops were generally less than 2 ft. d.b.h., whereas those that fell were somewhat larger. Tops were snapped off at a nearly uniform height of 60 to 75 feet at a diameter of approximately 1.0 foot. Across open reaches along Pack River below the bridge the trees fell to the north or northeast, but at the mouth of McCormick Creek trees were blown to the east and southeast. Above McCormick Creek some blowdown was to the south and southwest.

All of these clues suggest strong erratic winds just before the fire and the presence of strong fire whirls building and collapsing randomly in the area surrounding the Pack River bridge (fig. 17).

The sequence of events leading to the destruction of the bridge was also examined. The fire burned out both approaches and left the center span intact with some of its paint hardly scorched. The metal plate treads on the approaches were found draped from the concrete piers to the ground, indicating that as the wooden stringers and decking collapsed, temperatures had reached 1,200° F. This temperature level is not unusual in a fire.

Laboratory tests showed the design of the approaches provided sustained combustion in the space between stringers, and the approaches could have continued burning after the main fire had passed. The burning period probably extended over many hours until the decking broke up and the stringers collapsed. Then an increase in heat occurred as the material piled up on the ground, resulting in a period of flaming combustion followed by a long period of glowing combustion. Both types of burning contributed to the spalling of the concrete piers. Additional information on the Pack River bridge is provided in Appendix 3.

Figure 17. – Fire destruction at Pack River Bridge.

CONCLUSIONS

The spectacular run of the Sundance Fire on September 1, 1967, appears to have been a result of the combination of dry fuels from a sustained drought, low humidities for over 72 hours, increasing winds sustained for a period of 9 hours, and a 4-mile active fire front existing on the morning of September 1. The fire advanced 16 miles in 9 hours and created spot fires 10 to 12 miles northeast of the place of origin. Spotting activity increased during the day, reaching a maximum intensity during the period of highest winds in the late afternoon. Whereas spot fires early in the day contributed to the fire spread, late in the day a multitude of firebrands created fuel voids leading to the breakdown of the main front and contributing to the fire's termination. Other factors influencing the decreasing rate of spread were the increasing humidity after 2200, the decreasing wind after 2200, the downslope direction of burning, and to some degree the disruption of fuel continuity due to prior logging activities in the area.

The average rate of spread ranged from 1 to 6 m.p.h. with brief periods of spread rates having higher or lower values. The fire intensity built up to 22,500 B.t.u./sec.-ft. of fire front and was releasing nearly 500 million B.t.u./sec. A convection column rose to 35,000 ft. Extensive firebrand activity and debris were transported from the fire. These brands were either lifted as high as 18,000 feet and transported by the wind or carried in vortices produced by the wind blowing around the convection column. Fire-induced winds could have been greater than 95 m.p.h., and caused the extensive tree blowdown.

Fire buildup indices rated the conditions as "extreme" and spread indices forecast agreed reasonably with actual conditions. The averaged spread index for September 1 was "very high" and when combined with a buildup index of "extreme" produced a rating of "extreme fire danger." The National Fire-Danger Rating System Handbook describes it as:

EXTREME. — *Fires under extreme conditions start quickly, spread furiously, and burn intensely. All fires are potentially serious. Development into high intensity burning will usually be faster and occur from smaller fires than in the very high danger class. Direct attack is rarely possible, and may be dangerous, except immediately after ignition. Fires that develop headway in heavy slash or in conifer stands may be unmanageable while the extreme burning condition lasts. Under these conditions the only effective and safe control action is on the flanks until the weather changes or the fuel supply lessens.*

This very aptly described the Sundance Fire. The present rating system estimated the conditions properly and provided warnings of what could be expected.

This analysis of the Sundance Fire did not reveal any phenomena incompatible with existing knowledge and principles. The extension of laboratory findings and theoretical developments to a field situation resulted in estimates of burning rates, fire intensities, firebrand ranges, and induced windspeeds which are realistic. Evidence of various phenomena gathered during this study has heightened interest in additional research that will provide fuller explanations of such items as vortex generation, firebrand propagation, and spot fire ignition characteristics. The research people assigned to this study have gained valuable experience and we hope our interpretations will be useful and informative to other research and fire control personnel.

APPENDIX 1:

FUEL DETERMINATIONS USED IN THE ANALYSIS

As stated in the text, the fuel complex on the 55,910 acres burned by the Sundance Fire was divided into three levels: ground litter, brush, and crown material. The crown material consumed was composed of foliage and branches under 1/8-inch diameter based on observations made in the field. The brush level quantity was field sampled and the maximum size involved in the fire front was set at one-fourth inch. The ground litter was sampled in the field at two locations and visual estimates were made throughout the area. Because of findings in laboratory work on fuel consumption, the quantity of the total litter fuel involved in the front was set at 20 percent.

The crown weights were calculated on the basis of timber inventories made by the U. S. D. A. Forest Service. An assumption that State and private lands contain about the same variety of timber types was made after information received from agencies in Idaho had been reviewed. The number of acres occupied by each cover type on Forest Service land, based on the 1961 forest inventory, is as follows:

Cover type	Trees 5 inches d.b.h. and above	All Forest lands
	Acres	Acres
Larch	4,924	5,849
Alpine fir	3,636	3,636
Spruce	1,892	3,508
Hemlock	1,077	1,238
Douglas-fir	798	883
White pine	694	726
Cedar	670	710
Lodgepole pine	395	395
Ponderosa pine	170	170
Total	14,256	17,115

A study by Fahnestock (3), relating timber volume to slash weight, provided estimates of the crown fuel. First, average timber volumes for the Kaniksu Working Circle were determined by the following d.b.h. classes: 5 to 9 inches, 9 to 11 inches, 11 to 15 inches, 15 to 19 inches, and over 19 inches. Crown weight per acre was then determined from Fahnestock's study for each d.b.h. class using trees of average d.b.h. to represent each class. The weight of needles was calculated assuming 24 percent of the crown weight is foliage. Branches less than one-eighth inch in diameter were assumed to make up 6 percent of the crown foliage. The weight of crown fuel less than one-eighth inch in diameter was calculated as 30 percent of the crown weight. (These percentages were derived by weighting averages by volume for each species present in the Sundance Fire area.)

Crown weights (ovendry basis) for all species in the area are as follows:

Timber size class	Crowns	Foliage	Foliage plus branches <1/8"
Inches	(lbs./acre)	(lbs./acre)	(lbs./acre)
5-9	4,320	1,037	1,296
9-11	3,870	929	1,161
11+	4,830	1,333	1,630
Total	13,020	3,299	4,087

A field sample was taken on a 1/10-acre plot near the confluence of Young's Creek and Pack River in a stand of white pine and Douglas-fir appearing typical of timber in that area. All trees were tallied by species and 1-inch d.b.h. classes. Crown weights were calculated from relationships between tree d.b.h. and crown weight (4). Dry-weight estimates per acre are as follows:

Species	Foliage	Foliage plus branches <1/8"
	(lbs./acre)	(lbs./acre)
White pine	3,620	3,700
Douglas-fir	5,360	6,800
Total	8,980	10,500

This plot contained a heavier loading than determined for the fire area as a whole and was used to represent near maximum conditions. The figure used for average loading did not contain crown fuel for trees under 5 inches d.b.h. and probably should be somewhat higher.

A 1/4-milacre plot near Brown's Mill at the northeast end of the fire provided an estimate of the brush level. The ovendry weight was 5,400 lbs./acre of subordinate vegetation. Brush conditions were probably quite variable over the entire area but this plot, appearing typical of the area, was used as an average.

Ground litter was sampled at two locations; one near Brown's Mill and the other at the southwest end of the fire area near Coolin. These 1/4-milacre plots yielded the following loadings (ovendry basis):

	Brown's Mill (lbs./acre)	Coolin (lbs./acre)
Branches		10,040
Duff	17,000	23,880
Buried wood	23,040	
Humus		7,680
Total	40,040	41,600

These forest floor plots should be representative of much of the Sundance area although considerably lower loadings existed in some areas. Moisture content was determined by ovendrying as follows:

Fuel	Moisture content (Percent)
Green foliage	
White pine	144
Hemlock	148
Brush	
Green and some dead brush	67
Snowberry*	54
Forest Floor	
Entire floor (Coolin area)	20
Ponderosa pine litter layer*	8
Surface duff under spruce*	10
Dead branches on spruce*	12

**Samples collected and handled on the Priest River Experimental Forest by C. Carpenter.*

The moisture content of logs in the Hellroaring Creek area was sampled. Logs 3, 6, 12, and 18 inches in diameter were sampled for center and outer moisture contents. These measurements provided some indication of the effect of the moisture depletion for the season.

Species	Log diameter (Inches)	Outer moisture content (Percent)	Center moisture content (Percent)
White pine	3	8.6	8.6
Douglas-fir	6	32.4	37.4
White pine	[illegible]	15.2	14.9
Douglas-fir	12	12.7	29.7
Cedar	[illegible]	12.2	26.0
Cedar	[illegible]	11.6	27.3

APPENDIX 2:

METEOROLOGICAL FACTORS IN THE FIRE RUN

The account of the Sundance Fire in the text of this paper has emphasized the influence of the weather conditions, particularly those that produced the unusually strong winds that were a determining factor in the fire's phenomenal run. In this section we will first look at the general weather situation that existed over North America and the eastern Pacific Ocean, and then pay special attention to the relation of upper-air and surface winds in the vicinity of the fire. Comments on the relative humidity are also included.

The Large-scale Weather Situation

For the general weather picture, we will refer to a series of maps depicting atmospheric conditions at about 10,000 ft. m.s.l. (figs. 18 through 22). Maps at this level represent the general airflow and temperature pattern in the lower troposphere, largely free of irregularities induced by local terrain effects in this area.

The solid lines on these maps are height contours; these connect points of equal height (m.s.l.) at which an atmospheric pressure of 700 millibars (mb.) is reached, in analogy to contours on topographic maps (which give heights of the ground surface). The patterns shown by this form of depiction are nearly identical to the isobaric (equal-pressure line) patterns that would be found at a fixed height of 10,000 ft. m.s.l. The contours are drawn for 30-meter intervals and are labeled in tens of meters. The dashed lines are isotherms, drawn at intervals of 5 degrees Celsius. In addition, the winds observed at several individual stations are plotted in conventional symbolic form. That is, the windspeed is proportional to the number of barbs on the tail of an arrow (head not shown). Each full barb represents 10 knots (or 11.5 m.p.h.); a half barb indicates 5 knots. The tail of the arrow points in the direction from which the wind is blowing.

From the wind arrows in these maps, the airflow at 700 mb. is seen to be approximately parallel to the adjacent height contours. The windspeed, at a given latitude, is approximately inversely proportional to the contour spacing. Thus, the steeper the height gradient, the greater the windspeed in that area. In the present discussion, we will substitute the term "pressure gradient," which may be more dynamically descriptive.

The first map (fig. 18) depicts conditions on the morning of August 30 and illustrates a rather abnormal pattern, characteristic of much of the summer of 1967. The dominant pressure features seen here are (a) a strong, extensive warm ridge over the Western United States and Canada and (b) a deep trough and low center in the eastern Pacific area. This trough has been stationary for 3 days. Between the ridge and trough there is a strong pressure gradient. Over the interior Northwestern United States, winds are very light; the map shows a tendency for slow northward movement of warmer air.

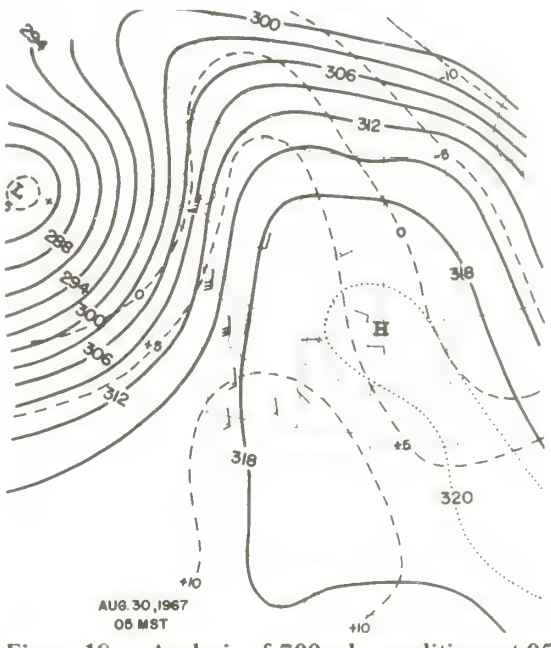


Figure 18. – Analysis of 700-mb. conditions at 0500 m.s.t. August 30, 1967. For explanation of symbols in figures 18-22, see text. Small circle in northern Idaho is approximate location of Sundance Fire.

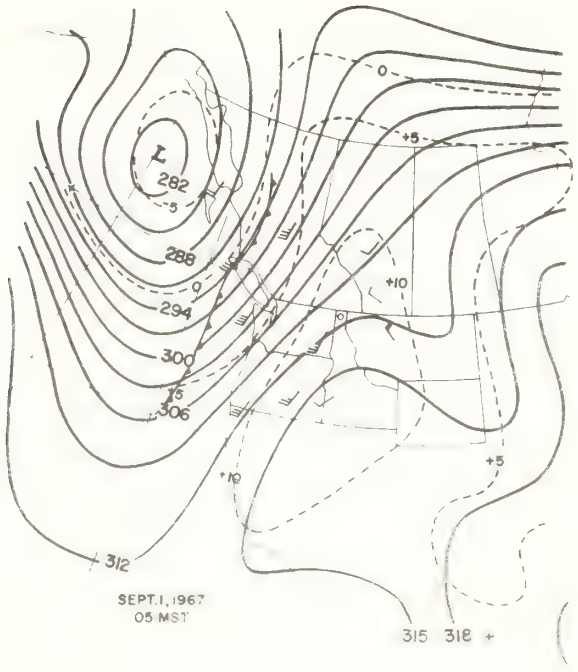


Figure 19. – Analysis of conditions at 0500 m.s.t. September 1, with concurrent surface position of cold front shown by sharp-toothed line.

In comparison, the "normal" 700-mb. flow over the Pacific Northwest at this time of year is rather zonal (west-to-east), with a slight trough along the Washington-Oregon coast and only a slight ridge over the Canadian Yukon. The "normal" refers to conditions averaged, and thus smoothed, over the period of a month. Nevertheless, the anomaly in the pattern on August 30, 1967, is outstanding.

Twenty-four hours later (map not shown), eastward movement of both the upper pressure trough and ridge had resumed but the area of highest temperature remained stationary over the West. The pressure gradient and observed winds near the British Columbia-Alaskan coast weakened somewhat, while a slight increase appeared over the Washington-Oregon area. A tendency for slow northward movement of warmer air continued over the interior Northwest. Resumption of the trough's movement was in response to a sequence of larger scale, Northern Hemispheric circulation features, whose complexity is beyond the scope of this paper.

The second map (fig. 19), an additional 24 hours later at 0500 m.s.t. (P.d.t.) September 1, shows continued eastward movement of the upper trough. At this time, a portion of the western ridge persisted over the Great Basin area. These two factors brought an increased pressure gradient in the Washington-Oregon area; there were southwesterly winds of about 40 knots near the coast. The speeds approached 25 knots in northern Idaho. Warm air persisted over the interior Northwest, but colder air associated with the trough had increased the temperature gradient across western Washington and Oregon.

Superimposed on this map as the standard sharp-toothed line, is the current (0500) surface map position of a cold front (or possibly an occluded front) that had been moving slowly eastward toward the Pacific Coast. This front is weak, and no pronounced temperature contrast corresponding to it can be found at the 700-mb. level.

By 1700 on September 1 (fig. 20), we see that the strongest pressure gradient has shifted further southeastward. This has been

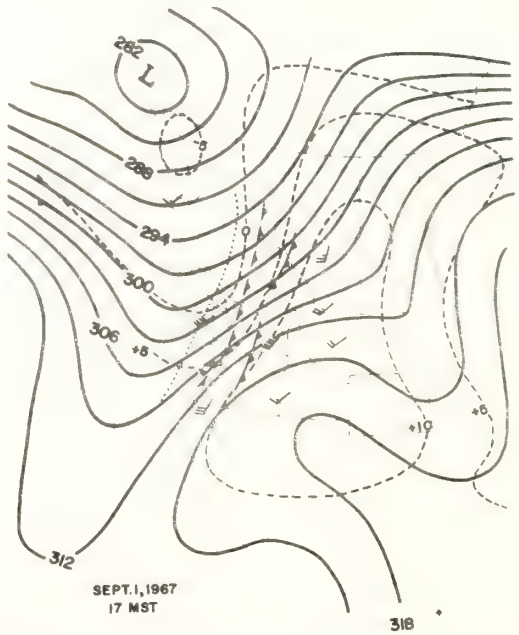


Figure 20. – Analysis of conditions at 1700 m.s.t. September 1, with surface cold fronts shown as in figure 19, except that dissipating Pacific front is shown in dashed form. The frontal position 6 hours earlier is shown by dotted line.

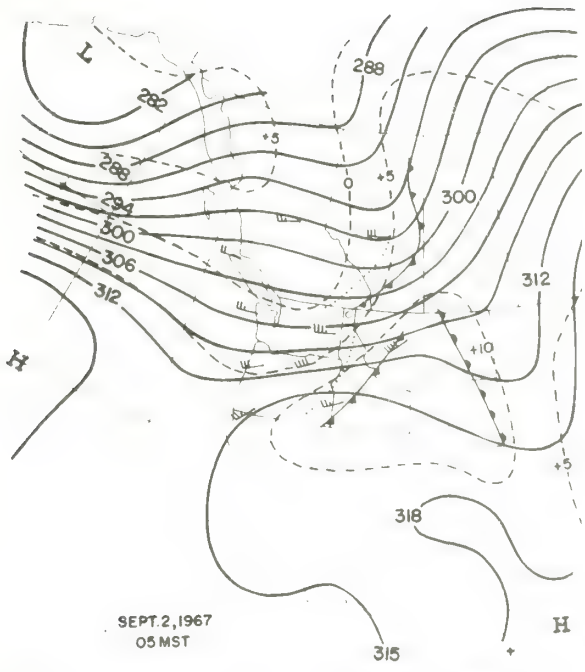


Figure 21. – Analysis of conditions at 0500 m.s.t. September 2, with surface fronts shown. Warm front is shown by round-toothed line.

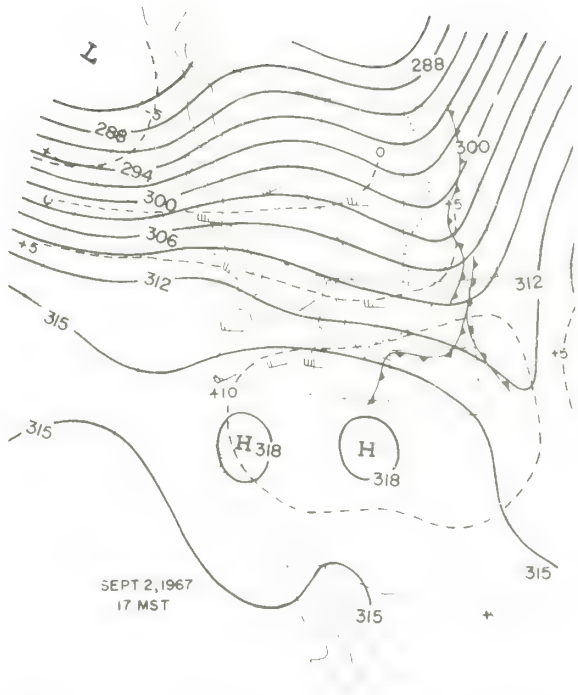


Figure 22. – Analysis of conditions at 1700 m.s.t. September 2, with surface fronts – cold, warm, and occluded – shown.

brought about by (a) further erosion of the ridge over western Canada as the trough pushed inland, and (b) a slight diurnal increase in the strength of the ridge in the Great Basin area. Southwesterly winds of about 35 knots are now indicated in northern Idaho, while 45 to 50 knots are observed upwind in northwestern Oregon.

At the surface, the weak Pacific front has moved inland across British Columbia and western Washington. (Position 6 hours earlier is given by dotted line.) However, by this time, a new cold front has apparently developed east of the Cascades in Washington-Oregon; this is related to increased juxtaposition of the cool and warm air masses (as indicated by the increased temperature gradient in figure 20). Also, a separate, more pronounced, cold front has apparently developed in the southeastern British Columbia area.

Twelve hours later, at 0500 on September 2 (fig. 21), we find the trough has progressed further eastward across western Canada and has dug into the northern portion of the western United States ridge. The offshore portion of the trough has flattened. Airflow over the northwest has thus become more westerly, and the zone of strongest pressure gradient and related wind has moved southward of the northern Idaho area. At the surface, the original Pacific front has dissipated, while the two newly defined cold fronts in Canada and the United States continue to move eastward, generally steered by the upper flow, retaining separate identities. The southern portion of the Canadian front has lagged behind that in the United States. Some light showers and thunderstorms have occurred with the Canadian front, but there have been none thus far with the United States front. Part of northern Idaho appears to be in a region between these fronts. Such frontal detail, possibly induced by topography, is not reflected in the upper air analysis, which is based on observations at stations about 250 to 300 miles apart.

The final map in this 700-mb. series (fig. 22) shows conditions 12 hours later at 1700 on September 2. The pressure gradient over the northwestern United States has decreased further, and flow is now westerly. Little re-

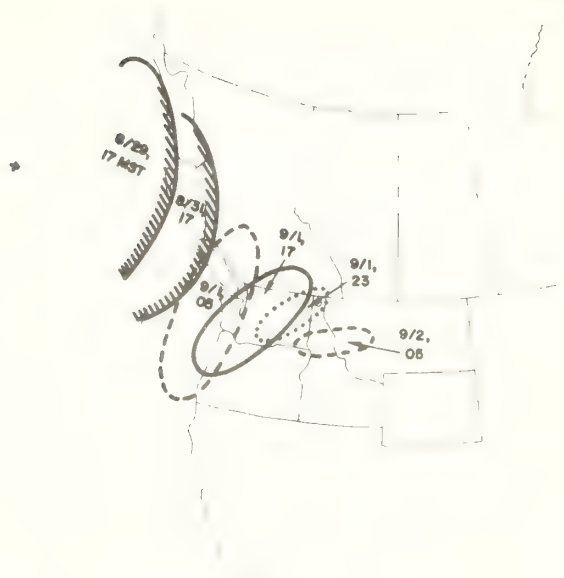


Figure 23. – Areas of strongest winds (40 knots or greater) at 700 mb., August 29 to September 2, 1967.

mains of the trough in the west, while a tendency for ridging appears again. The surface fronts, distorted by topographic barriers and perhaps other factors, have moved well to the east. Light thundershowers occurred during the late morning or afternoon of September 2 in eastern Montana, with only showers to the north in Canada.

Using the indications of the preceding charts (and several not shown here), the areas of strongest wind aloft, preceding and during the fire run, are summarized in figure 23. A speed of 40 knots (46 m.p.h.) has been chosen as the lower limit for inclusion. The outlined areas were defined on the basis of the observed winds and the analyzed pressure gradients. A gradual southeastward to east-southeastward progression of strongest wind is evident. The zone of such wind passes through the northern Idaho area at the time of the 2300 P.d.t. observations on September 1.

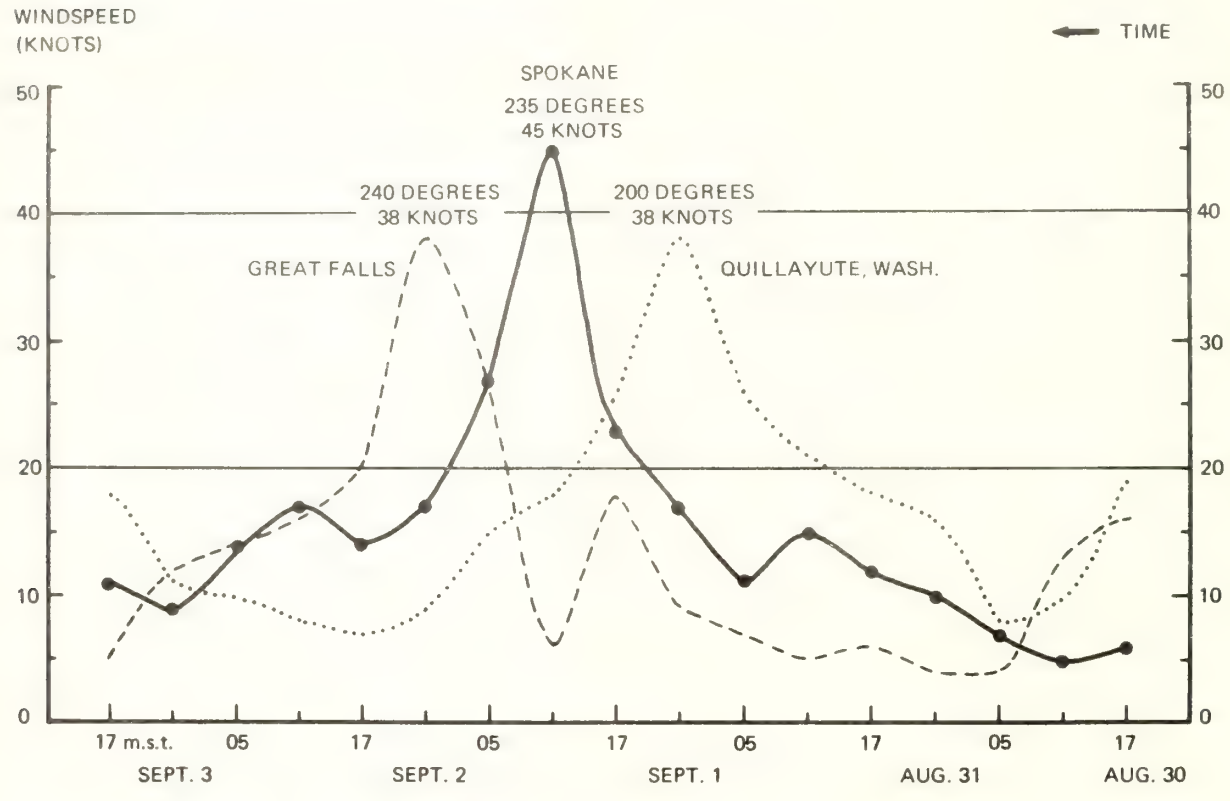


Figure 24. – Time graph of mean windspeed in the 5,000 to 7,000-ft. m.s.l. layer at Spokane and two adjacent stations, August 30 to September 3, 1967. (Note that time proceeds from right to left in this and the following three figures.) Wind direction in degrees is also shown for the maximum speed for each station.

Upper-Air and Surface Winds in Northern Idaho Vicinity

We may view the winds aloft from another standpoint, in the form of a time graph for an individual station. Figure 24 shows such a graph of the mean windspeed in the 5,000 to 7,000-ft. m.s.l. layer for Spokane, 70 statute miles southwest of Sundance Mountain. For comparison, the corresponding windspeeds are given for two adjacent upper-air stations (to the west and east). These stations are Quillayute, on the northern Washington coast, and Great Falls, Montana. A pronounced peak in speed in the 5,000- to 7,000-ft. layer is seen to have occurred at all three stations. The peak at the coastal station occurred approximately 12 hours before that at Spokane, whereas the peak at Great Falls occurred about 12 hours after that at Spokane. The peak speed in this layer, 45 knots (from the southwest), is highest at Spokane; however, nearly as high a speed, 43 knots, was observed in a lower layer (2,000-4,000 ft. m.s.l.) at the coastal station. This diagram gives further evidence that the strong lower level winds in the Sundance Fire vicinity were a more or less sustained, broad-scale, moving feature which, at least in retrospect, was trackable.

Sustained windspeeds of 40 to 45 knots at 5,000 to 7,000 ft. m.s.l. appear to be exceptional in the northern Idaho area during the fire season. This is the impression gained from an examination of Spokane winds-aloft reports for the period June 15 to September 15 of the years 1957 through 1967. Speeds of 38 knots or greater at 5,000 feet appear to occur on an average of only 2 days per season (based on four wind soundings per day). In all but one of 12 actually observed cases in this 11-year period (wind soundings were made only three times per day during five of the years), the days with such windspeeds occurred in June or September. The wind direc-

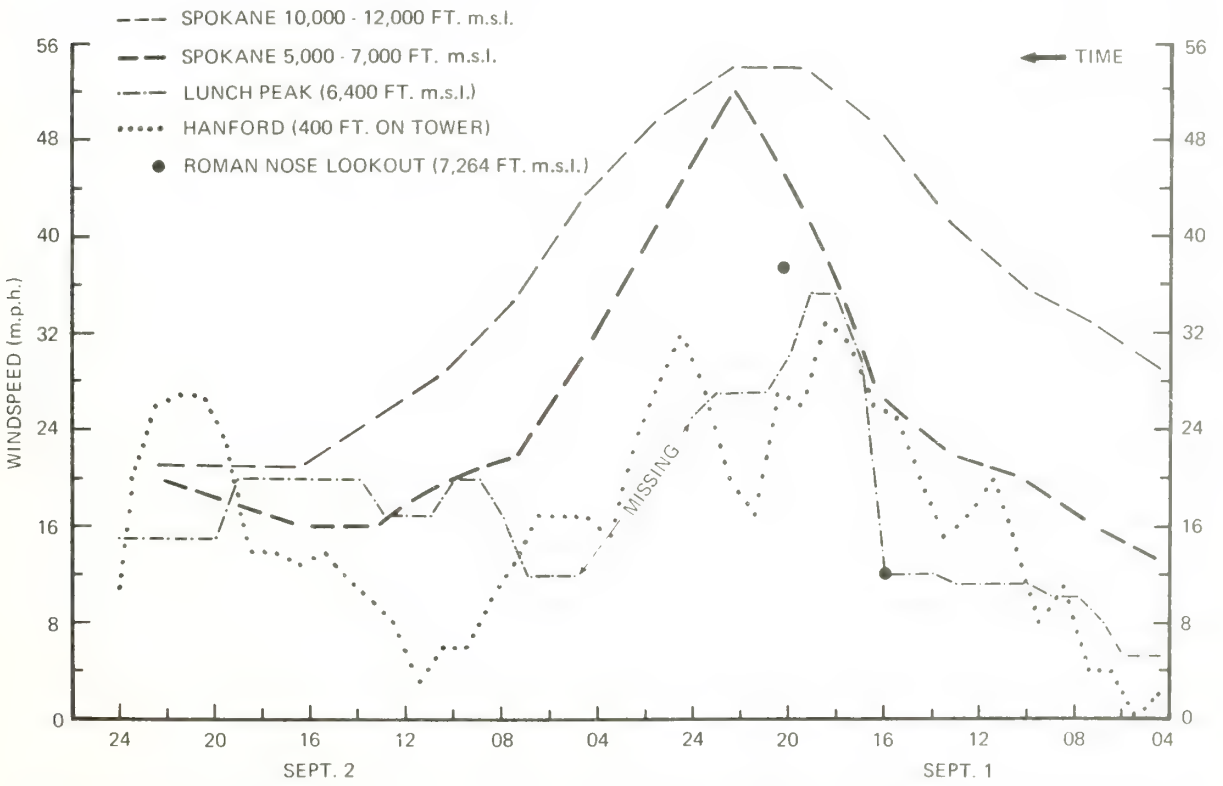


Figure 25. – Time graph comparing free-atmosphere windspeeds at Spokane and surface or tower windspeeds at several observation points, September 1-2, 1967.

tion in all but one case was southwesterly or west-southwesterly, with some sort of upper trough located near the Washington coast.

We have thus far looked at wind indications from upper-air observations. An obvious question is how do these winds aloft relate to those actually observed or expected at ground- or tree-level locations. Winds in mountain areas may, of course, vary considerably according to exposure to the general airflow. In addition, surface friction acts to reduce the windspeed near the ground, but terrain-induced turbulence (proportional to gradient windspeed) may bring strong gusts. Locally, winds may be increased by terrain-enforced convergence of airflow. Figure 25 compares the free-atmosphere winds observed above Spokane with the winds at several surface stations.

In the Sundance Fire vicinity, hourly wind data were available, except for several nighttime hours, from Lunch Peak, at 6,400 ft. m.s.l. 20 miles to the southeast. A mobile fire-weather station, sent from Boise, was in operation here for the Plume Creek Fire. A rather abrupt rise in the Lunch Peak windspeed is noted between 1600 and 1700 P.d.t. on September 1. Winds from the southwest soon reached an average of approximately 35 m.p.h. at 1800 and 1900 P.d.t.; gusts (not plotted in the diagram) were up to 50 to 55 m.p.h. for several hours.

Roman Nose Lookout, at 7,264 ft. m.s.l. on the northern edge of the fire, had a 12 m.p.h. southerly wind at the regular 1600 P.d.t. fire-weather observation time; a steady speed of 35 to 40 m.p.h. from the southwest was reported at 2015 P.d.t. (note point plotted in figure 25). A lookout atop Mt. Henry (7,235 ft. m.s.l.), in extreme northwestern Montana, reported winds averaging 40 m.p.h. and gusting to 60 m.p.h. (time not given).

Among the mountaintop fire-weather stations reporting once daily, four of the seven in northeastern Washington (at elevations ranging between 3,800 and 5,900 ft. m.s.l.) had windspeeds between 27 and 33 m.p.h. at 1600 P.d.t. Speeds at five such stations in the Idaho panhandle (at elevations between 5,200 and 6,400 ft. m.s.l.) were as yet only between 12 and 16 m.p.h. To illustrate possible terrain-exposure effects, Squaw Peak, Montana (at 6,200 feet), nearby to the southeast, had 29 m.p.h. winds at this time.

The Lunch Peak (and Roman Nose Lookout) windspeeds fit in reasonably well with the 5,000- to 7,000-ft. wind trend at Spokane during the late afternoon and early evening of September 1. The same can be said for the winds atop a 400-ft. tower at the Hanford A.E.C. Works, ground elevation 700 ft. m.s.l., about 120 miles southwest of Spokane. The available Lunch Peak and Hanford speeds differ considerably, however, from those of the free-atmosphere winds at Spokane later in the evening. This difference is probably associated with variations in the vertical, turbulent transfer of momentum through the "friction layer." This layer would extend mainly to near 5,000 ft. m.s.l. at Spokane and to correspondingly higher altitudes above the mountainous area in northern Idaho. Although reference is made in this paper to free-atmosphere winds at 5,000 ft. m.s.l. in the Sundance area, such winds are largely hypothetical.

It may be well to clarify here the relationship between the strong winds in the Sundance area and the movement of a cold front. The strong, or relatively strong, and gusty surface winds observed in eastern Washington and northern Idaho on September 1 began by middle or late afternoon. This onset took place, at high and low elevations, approximately 100 to 150 miles in advance of the cold front that had developed east of the Cascades. Cooler-air movement, representing a gradual change of airmass, was, however, already accompanying these prefrontal winds. The front in this case thus appears to represent a secondary steepening of horizontal temperature gradient imbedded within a broader gradient. The peak in 5,000-ft. m.s.l. free-atmosphere windspeed, which was reached in the late evening, occurred near or slightly behind the surface map projection of this eastward-moving front. But, as indicated earlier, the front was rather diffuse or undetectable in northern Idaho and extreme eastern Washington.

In the absence of more detailed data coverage, the actual effect of this diffuse front (or frontal zone) on the Sundance surface winds remains a matter for speculation. It is, however, apparent that the front alone could not have accounted for the unusually strong,

gusty winds which persisted for several hours. These winds were ultimately dependent upon the exceptional summertime pressure gradient that existed in the lower levels of the troposphere. The extent to which winds of gradient strength or greater were experienced near the surface would, of course, vary, as previously discussed. Turbulence commonly attending a cold front may or may not have been an important triggering factor in this case.

The strong pressure gradient and the cold front, both associated with the approaching trough, may be regarded as individual but related parts of a weather system. Basic to such a system is the juxtaposition of two different (warm and cool) airmasses. The upper tropospheric jet stream, whose core in this case was at only 25,000 to 30,000 ft. m.s.l., would also be part of this system. Moving eastward, its axis at 2300 P.d.t. September 1 was about 100 miles northwest of Spokane and the Sundance area. The windspeed over Spokane was approximately 80 knots (interpolated), having increased from 60 knots at 1700 P.d.t. Such a jet could, through dynamic processes, possibly effect a vertical transfer of momentum (and other properties) to the lower troposphere. This would occur within a frontal zone sloping below the jet's core, in the form of a dry-adiabatic sinking of air from the upper tropospheric portion of the zone (located many miles upwind of its lower portion) (6). Some evidence was found supporting the presence of such an effect in the Sundance case, but was regarded as inconclusive.

The estimated hourly free-atmosphere (gradient) windspeeds at 5,000 ft. m.s.l. in the Sundance area, used in this fire report, are given in figure 26. These speeds are based upon the 6-hourly upperwind observations at Spokane. Observed surface winds, referred to earlier, were used as a guide in allowing for a slight timelag in adapting a vertical cross-section analysis of Spokane upper winds (not shown) to the Sundance area. The lag, adjudged also according to spatial differences in pressure gradient on the 700-mb. maps, did not exceed 1 hour and was adjudged to be zero after the time of maximum wind.

Humidity

Also plotted in figure 26 is a curve of estimated "modified" free-atmosphere relative humidity at 5,000 ft. These humidity values are a compromise between those in the free atmosphere and those observed near ground

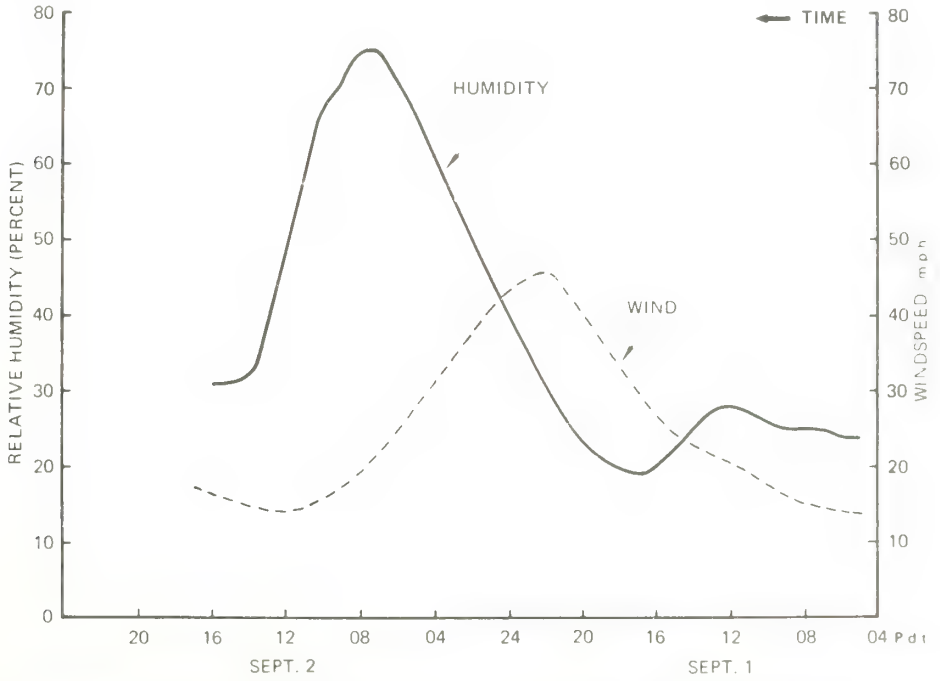


Figure 26. – Time graph of estimated free-atmosphere windspeed and "modified" free-atmosphere relative humidity at 5,000 ft. m.s.l., Sundance Fire area, September 1-2, 1967.

level on a ridge or mountaintop. Relative humidity is, of course, a function of both temperature and actual water-vapor content of the air. The values given here were derived by use of Spokane surface and upper-air observations and the hygrothermograph charts from both Gisborne Mountain Lookout (about 10 miles south of the Sundance Fire area) and Big Spot mobile weather station (about 25 miles north of Sundance). Good consistency was found among the temperature and vapor pressure tendencies from these data sources. The Lunch Peak data, however, were not used here; the observed temperature values and behavior showed discrepancy with those at the above stations and at 6,424-ft. Sunset Peak, Idaho (70 miles SSE of the Sundance Fire), and were considered unrepresentative of the general area.

A relative humidity threshold of about 30 percent has been found empirically by some researchers to be critical in the preconditioning of fine fuels. The estimated relative humidity for the Sundance Fire environment is seen to have remained below 30 percent on September 1 until after 2200 P.d.t., about the time of maximum estimated gradient wind. A steady increase then occurred, raising the humidity to 75 percent the following morning. For comparison, the low relative humidity that persisted for several preceding days and nights is shown in figure 27. The relative humidity increase (September 1-2) was related primarily to the decrease in "modified" free-atmosphere temperature (to 51° F. at 5,000 ft. m.s.l.), rather than to any large increase in vapor content of the air as compared with preceding nights.

Concluding Remarks

In summary, we have described the general weather situation associated with the Sundance Fire run and have examined more specifically the related wind and relative humidity. Additional research, not reported here, examined other considerations stated in the literature to be possibly important in rapid or "explosive" fire spread. Primarily these are (a) vertical wind profile (change of speed and direction with height); (b) airmass instability; (c) subsidence; and (d) downdrafts from adjacent thunderstorms. The last-named factor may be safely regarded as absent in the Sundance Fire case. Findings with respect to the first three, not particularly crucial, will appear in a forthcoming separate, more complete meteorological paper.

The above-presented weather factors must be considered together with other factors, such as fuels and topography, in accounting for the fire behavior. With this in mind, it is nevertheless quite apparent that unusually strong winds occurred in the Sundance vicinity at a most unfortunate time.

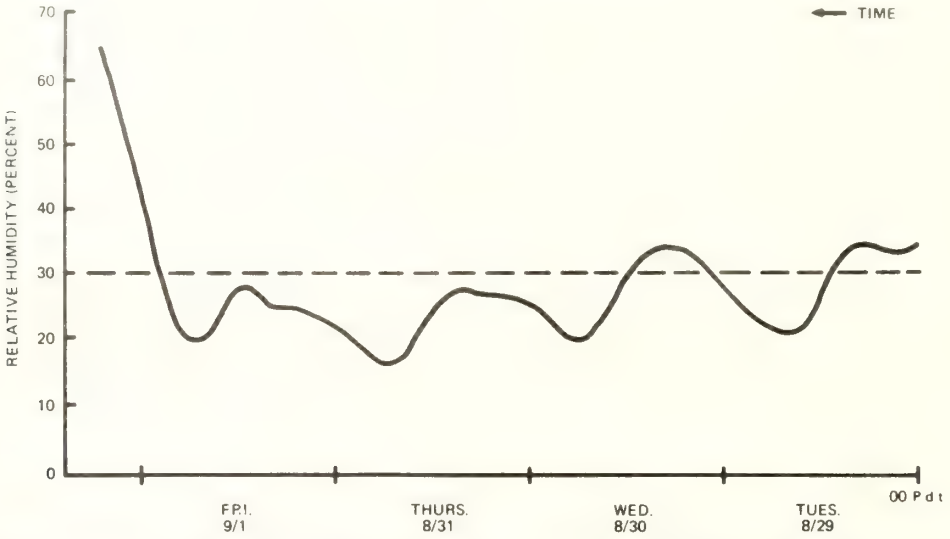


Figure 27. – Time graph of estimated "modified" free-atmosphere relative humidity at 5,000 ft. m.s.l., Sundance Fire area, for several days prior to and including September 1, 1967.

APPENDIX 3:

THE PACK RIVER BRIDGE AS AN AREA FIRE INTENSITY INDICATOR

The Sundance Fire burned with extreme intensity in many areas, as exhibited by rock spalling and complete burnout of ground fuels. The area where the fire crossed the Pack River is a notable example. Here, the visitor is awed by the coupled effects of high winds and intense fire activity. Nearly all the large trees — cedars and hemlocks — have been uprooted or broken and are lying charred among the grey ash remains of ground fuels. Also, the remains of the Pack River Bridge are mute evidence of the fire's passing. There has been much speculation about the intensity necessary to result in the complete burnout of the approach spans and distortion of the carbon steel plates covering the deck runway. This short study is intended to establish the relationship, if any, between fire intensity at the bridge and in the surrounding area.

Extent of Fire Damage to the Bridge

The bridge spans the Pack River in a nearly north-south direction near the McCormick Creek inlet as shown on the foldout map. Three connected segments make up the bridge: the center span resting on two concrete piers in the stream bed and two approach spans resting on concrete footing on the streambank. The design is shown in figure 28. The center span is 65 ft. long by 14 ft. wide. Each approach span is approximately 24 ft. long by 14 ft. wide. The decks of the approach spans are 6 inches thick, and are made up of laminated 2- by 6-inch boards. Strength is given to the deck by nine traverse beams 8- by 20 inches by 24 feet, spaced along the length of the span. Carbon steel plates 5/16-inch thick were also placed on the deck runways to provide traction and reduce wear. The primary structural material used was creosote-treated Douglas-fir.

Fire damage to the bridge was confined essentially to the approach spans; although there was evidence of burning at each end of the central span, the major portion of it was unscorched by the surrounding fire activity. Figure 17 (main text) shows the burnout of the north approach span. Figures 29 and 30 show other views of the bridge. Notice the unburned paint on the central span shown in figure 29. Figure 30 shows the complete burn-

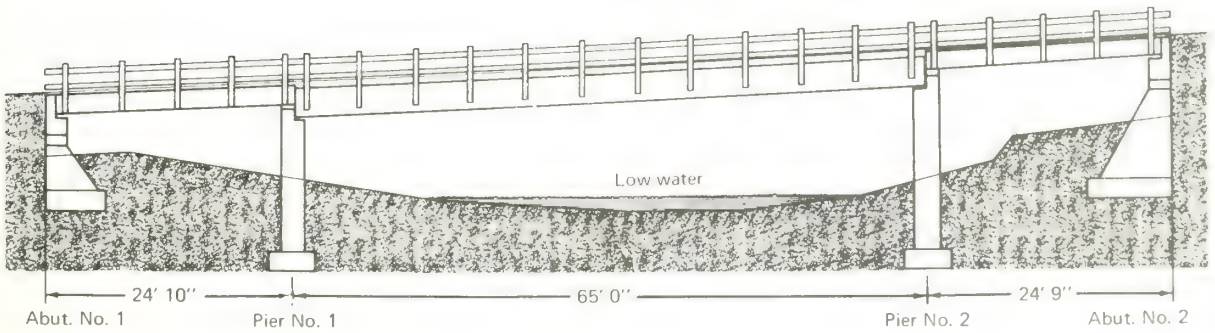


Figure 28. – Side elevation of Pack River Bridge.

Figure 29. – View of Pack River Bridge looking southeast.

Figure 30. – Burnout of north approach span, Pack River Bridge, showing distortion of steel surface plates.

out of one of the approach spans and the deformed steel plates. The other span is identical in appearance. It is apparent from the photograph that the steel plates had been sufficiently softened by the heat to conform to the shape of the surface they fell upon when the span gave way.

Hypotheses of Ignition and Burning

The probability of ignition of the bridge is of course dependent on the residence time of the fire in the surrounding area. Anderson[3] gives us a relationship between θ, the residence time in minutes, and D, the particle diameter in inches.

$$\theta = 8D$$

From evidence of burned limb stumps, 2 inches in diameter, we estimate a residence time in the surrounding fuels area of 16 minutes. Limbs of larger diameter would help sustain the residence time past 16 minutes; this would certainly be enough time to ignite the brush near the approach spans (the remains of this brush may be seen in figure 17). The burning brush would then act as an ignition source for the bridge.

The importance of closely positioned kindling fuels is demonstrated by the fact that fire damage to the central span was limited, owing to the absence of a nearby source of ignition. Except for occasional hot flames the region just above the creek bottom would be relatively cool compared to the surrounding area. We conclude that fire activity in the central span near the concrete piers was simply an extension of the fire in the approach spans. During the period of burning, winds near the bridge were predominantly upstream or downstream, that is, normal to the bridge, as evidenced by the creosote smoke deposited on the steel beams on either side of the central span. Consequently, we believe the fire traveled crosswise to the wind and simply burned out near the concrete piers. If there had been ignition on the windward side of the central span, more extensive damage would have occurred in that section.

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[3] *Anderson, Hal E. ~~Radiation model for~~ HEAT TRANSFER AND fire spread. U.S.D.A. Forest Serv., Intermountain Forest and Range Exp. Sta., Ogden, Utah. (In preparation.)*

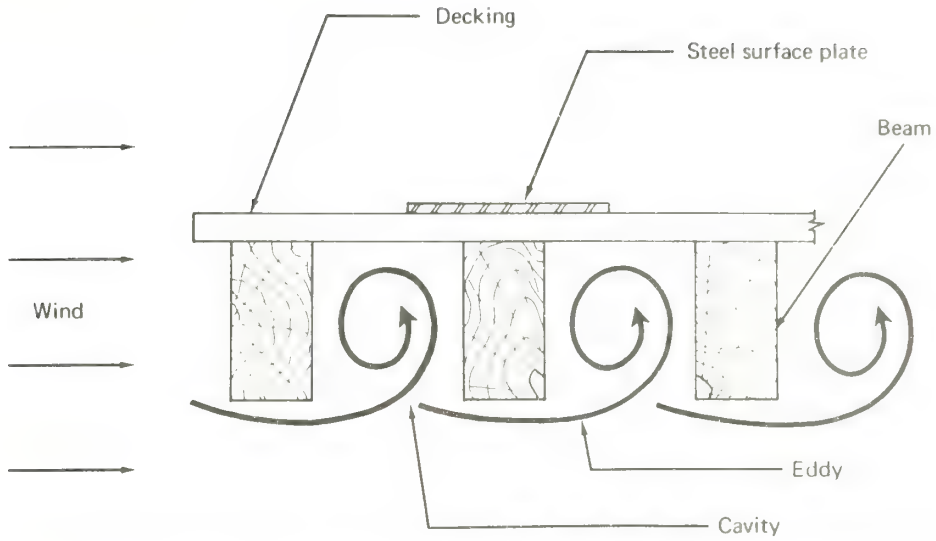

Figure 31. – Cross section of approach span of bridge, showing supposed pattern of wind eddy formation within cavities.

Once the bridge had been ignited, enhancement of the burning can also be attributed to the long rectangular cavities between the beams located below the bridge. It is hypothesized that wind blowing over these cavities perpendicularly to the beam axis or bridge direction produces eddies on the leeward side of the beams within each cavity, as illustrated in figure 31. As the windward side burns, flames are entrained into the eddies on the leeward side. Thus, combustion is propagated into the adjacent cavity. In this situation, only a limited amount of air is entrained into the cavity with the flames so that combustion of only a portion of the volatilized gases from the inside surface can be completed within the cavity. As the heat builds up, an overabundance of the volatilized gases is produced within the cavity. Thus, the proper fuel air mixture is not attained until the gases are swept out of the cavity into the outside air. However, just as these gases leave the cavity and begin flaming combustion they are entrained into the next cavity and so the cycle is repeated until all the cavities are burning. Notice also, in figure 31, that the two walls formed by the beams are advantageously located for enhancement of burning by reradiation between the walls.

There is no direct evidence to support the hypothesis that eddies were formed in the cavities below the deck. However, a reconstruction of the bridge fire under laboratory conditions gives us a qualitative examination of eddy production that could lead to support or rejection of the hypothesis. For our purpose a cross-sectional slice of the beam axis of the bridge-approach span is sufficient. Since a qualitative examination is all that is possible, there is no strict adherence to scaling. The deck is made up of 1½- by ½-inch white pine lumber and the beams are replaced by 2- by 4-inch Douglas-fir. Two coats of diesel oil were applied to the model to simulate the creosote treatment.

The simulated bridge section was placed in the wind tunnel with the wind flowing at right angles to the beam axis. To eliminate burning on the exposed cross-sectional faces it is necessary to cover both faces with sheet metal. Two bridge sizes were burned in the wind tunnel under identical conditions, the only difference being in the width. In the first test the bridge was 42 inches wide and in the second 17 inches. In both cases ignition by simulated ground fuels (excelsior) was on the windward side. Because of the size difference ignition was confined to the first few cavities in case 1 and extended over the entire bridge section in case 2.

Figure 32. – Model of bridge approach span (42-inch size) burning in wind tunnel.

These two cases simulated two possible levels of ignition. Although the ignition was different, the circulation patterns in the cavities are identical. In the photograph, figure 32, a similarity to the expected eddy patterns shown in figure 31 is evident. There is great likelihood then that eddy patterns were created in the cavities below the deck, enhancing the fire activity at the bridge.

Creosote preservative on the wood structures of the bridge and vegetation near the bridge approaches certainly contributed to the ignition process; however, the wind and the associated eddies produced within the cavities under the bridge are of greater importance. If there had been no cavities, it is likely that burning would have been greatly reduced except at the edges, resulting in much slower burning and possibly more unburned residue, rather than the complete burnout of the approach spans that actually occurred.

Winds at the bridge site were primarily fire induced and generated in the drainage in an area remote from the bridge. They were "indraft" winds resulting from strong convective upward flow at the generating source. These winds were sustained as other areas in the drainage burned, creating additional generators. Furthermore, there were enough other areas to sustain winds for the equivalent of at least four residence times, thus accounting for 1 hour of intense fire activity at the bridge site. This was certainly enough time for the bridge to have achieved sustained combustion without the necessity of continued sources of wind and heat. It is very likely that these indraft winds were present at the bridge because the creekbed acted as a relatively unobstructed trough for the flow of air.

Damage to Steel Runways

Heat transfer to the steel runways was sufficient to cause a large reduction in the tensile strength as evidenced by the distortion of the plates shown in figure 30. Considering the density of steel we may assume that it would deform appreciably under its own weight if it lost three-fourths of its peak strength. Examination of the variation in steel strength with temperature indicates that a reduction of strength of that extent would be achieved at 1200° F. This is in no way indicative of the temperature outside the immediate bridge area. Contrary to news reports, there is no evidence that the steel had reached the melting point, 2,800° F.

Conclusions

An examination of the bridge and the simulated bridge fire suggests that:

1. The bridge approaches were ignited by ground fuels.
2. Once ignited, the bridge continued to burn independent of the heat supplied by surrounding forest fire.
3. The bridge design contributed to the fire damage, since eddies formed by the wind normal to the bridge produced and captured pockets of burning gas on the underside of the bridge.
4. The distortion of the steel plates merely indicates that a fire was present long enough to heat the plates to 1,200° F. or more (but not up to the melting point, 2,800° F.)
5. The bridge fire is not an indicator of the intensity of the surrounding forest fire.

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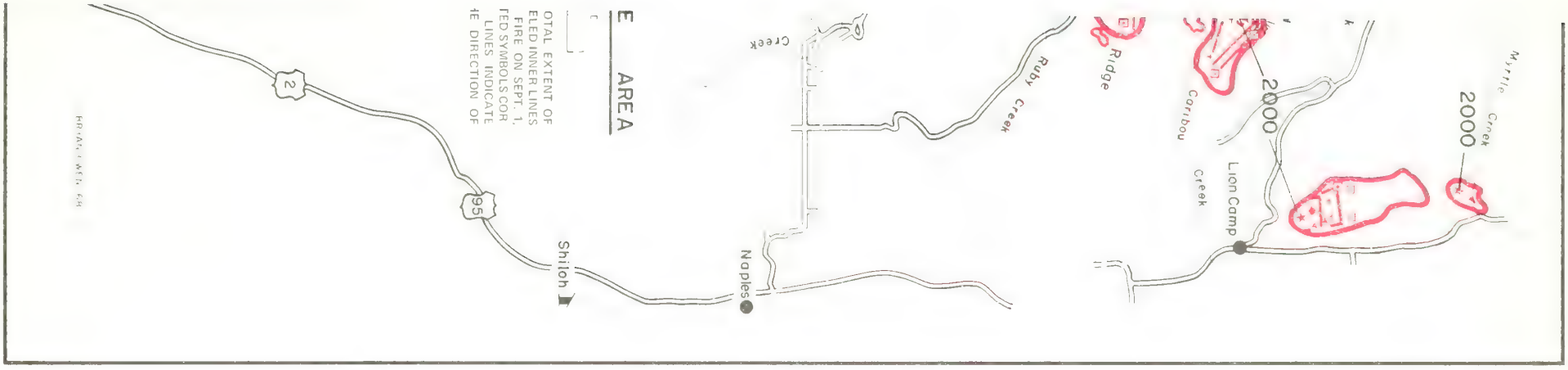

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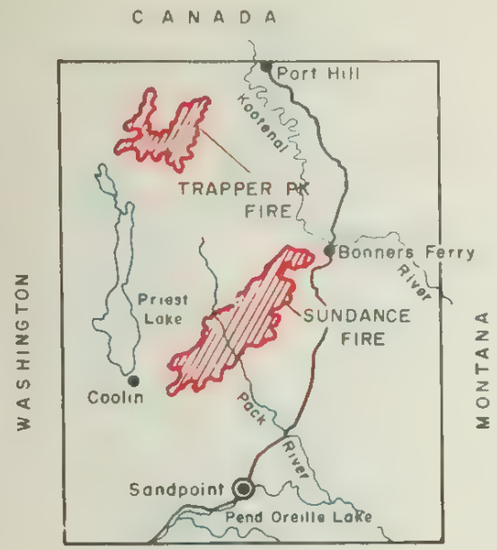

SUNDANCE FIRE AREA

SCALE IN MILES

OUTER SOLID LINE SHOWS TOTAL EXTENT OF BURNED AREA ON SEPT 3 LABELED INNER LINES SHOW HOURLY PROGRESS OF FIRE ON SEPT 1 EXCEPT WHERE NOTED ISOLATED SMALL FIRES OR RESPONDING TO FIRE EDGE LINES INDICATE SPOT FIRES BURNING IN THE DIRECTION OF THE ARROWS

BRIAN [illegible]

Anderson, Hal E.

1968. Sundance Fire: an analysis of fire phenomena. U. S. Dep. Agr., Forest Serv., Intermountain Forest and Range Exp. Sta., Ogden, Utah 84401. 39 pp., illus. (U. S. Forest Serv. Res. Pap. INT-56)

The Sundance Fire on September 1, 1967, made a spectacular run of 16 miles in 9 hours and destroyed more than 50,000 acres. This run became the subject of a detailed research analysis of the environmental, topographic, and vegetation variables aimed at reconstructing and describing fire phenomena. This report details the fire's progress; discusses the fire's buildup in intensity, the fuel complex through which it traveled, the wind and other atmospheric variables affecting the fire's behavior; and describes the processes that probably account for the tree breakage and blowdown, the long-range spotting, and the subsidence of the fire's run.

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FACTORS THAT AFFECT USE OF WOOD SIDING MATERIALS IN SINGLE-FAMILY HOMES

RESEARCH PAPER INT-57, 1968
Intermountain Forest and Range Experiment Station
Ogden, Utah 84401

THE AUTHOR

ROBERT E. BENSON is Marketing Analyst stationed at the Forestry Sciences Laboratory in Missoula, Montana. His career includes experience in forest and land use surveys, economic studies of timber production, and analysis of markets and marketing systems for wood products manufactured in the Rocky Mountain States.

Research Paper INT-57

FACTORS THAT AFFECT USE OF WOOD SIDING MATERIALS IN SINGLE-FAMILY HOMES

Robert E. Benson

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

AFLC HAFB OGDEN 2000

HIGHLIGHTS

- Wood siding was most common in northern and northeastern cities and was used least in southwest and southeast cities.
- About 46 percent of the siding used in homes surveyed was of wood-based materials.
- Fiberboard was the most widely used wood-based siding, accounting for about one-fifth of all siding used.
- Architectural requirements influence type of siding but not always material used.
- Builders recognize certain cost advantages and disadvantages of various sidings, but cost factors do not usually alter traditional geographic preferences.
- Most builders either select the siding for the home or limit the choice of siding they offer to buyers.
- Esthetic appeal and product improvement are keys to wood siding's market future.

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NEED FOR MARKET APPRAISAL

Exterior siding used on houses has until recently been limited to lumber, brick or other masonry, wood shakes, stucco, and several composition materials. During the past two decades, however, new siding products have been developed, particularly sheet and board materials including nonwood sidings of aluminum and plastics, as well as new types of wood-based sidings, such as fiberboard, plywood, and wood overlaid with nonwood materials. These new products have gained market acceptance because of changes in homebuilding design and techniques and the need to reduce installation and maintenance costs.

In view of these developments, an appraisal of the market outlook for siding is vital for planning by timber resource managers. The utilization of existing stands of timber and the regulation of species and quality depend in part on the types of products desired. Obviously, the species or qualities of wood needed for sawn lumber siding, wood shakes, fiberboard, and overlaid wood sidings vary greatly. Such an appraisal also is vital for manufacturers of wood products; they can best convert timber into desirable products when the market criteria their products must meet are clearly defined.

Any complete appraisal of the siding market must consider such factors as technological developments in products and trends in building activity, as well as the market criteria of builders and buyers. However, this study was limited to the following objectives:

1. Identifying geographic differences in metropolitan markets.

2. Determining the relative importance of builders, home buyers, and suppliers in selection of siding.

3. Identifying and evaluating the relative importance of various factors that constitute the market criteria for siding such as (a) appearance, (b) maintenance requirements and other performance characteristics, (c) availability and suppliers' services, (d) style and price of the home, (e) cost, including price and installation, and (f) home buyers' preferences and options.

4. Evaluating how well wood sidings meet the more important criteria identified and what changes are needed to improve their acceptance.

5. Appraising the market outlook for wood sidings.

The study is based on personal interviews with 82 builders in 20 cities throughout the continental United States. These cities were chosen at random from metropolitan areas with 100,000 or more population. Sample builders were selected from the yellow pages of the telephone directories. The study covers 5,243 houses built either in 1965 or 1966, depending on which year the builder was interviewed.

VARIATIONS IN USE

Wood-based siding accounted for about 46 percent of all siding used in the 5,243 houses covered in this survey and was the principal siding used in about 41 percent of these houses. Fiberboard was the leading wood-based siding used and brick the most common nonwood siding used. Builders often use one material for the principal siding and a second material for accent panels or gable ends, which is reflected in the following tabulation. For example, plywood was used mostly as a secondary siding; thus, it accounted for 4 percent of all siding used, but was the principal siding used in only 1 percent of the houses.

Material	Percent of all siding used	Percent of homes in which material was principal siding
Brick	28	29
Wood-based:		
Fiberboard	21	20
Shake	11	13
Lumber	9	7
Plywood	4	1
Overlaid lumber and plywood	1	<0.5
Subtotal	46	41
Other:		
Aluminum	9	10
Asbestos	4	4
Block	5	5
Stucco	8	11
Subtotal	26	30

Wood was the leading siding used in only five of the cities surveyed, brick in eight cities, stucco or block in four cities, and other materials in three cities (fig. 1). However, wood accounted for a significant share of siding used in most cities (fig. 2). Wood's share of the market was less than 10 percent of all siding used in only five cities. Individual builder use within cities varied considerably from these siding-use patterns. Wood is most often used in cities in the north and northeast, and used least in southwestern and southeastern cities.

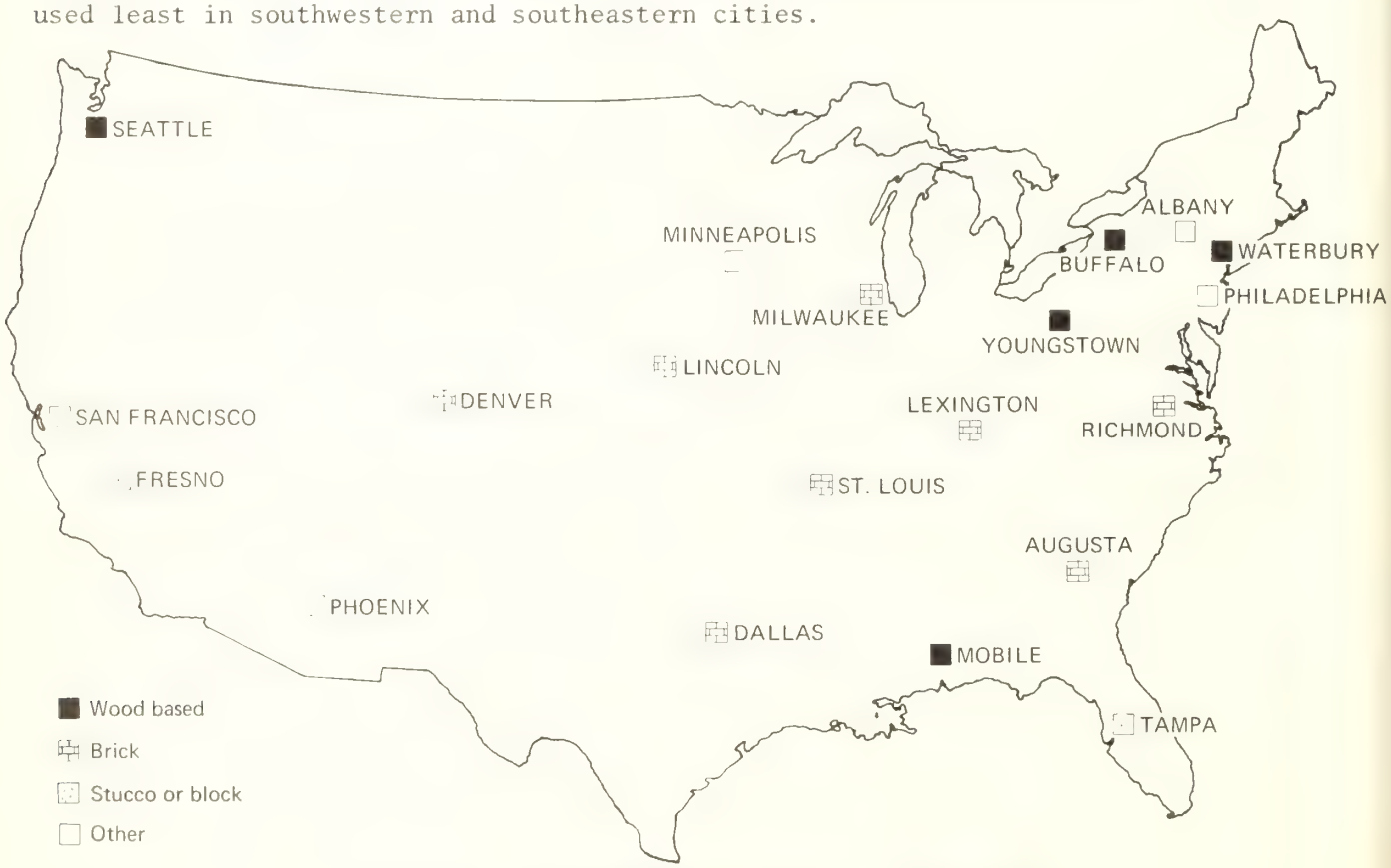

Figure 1.--Leading siding materials in sample cities.

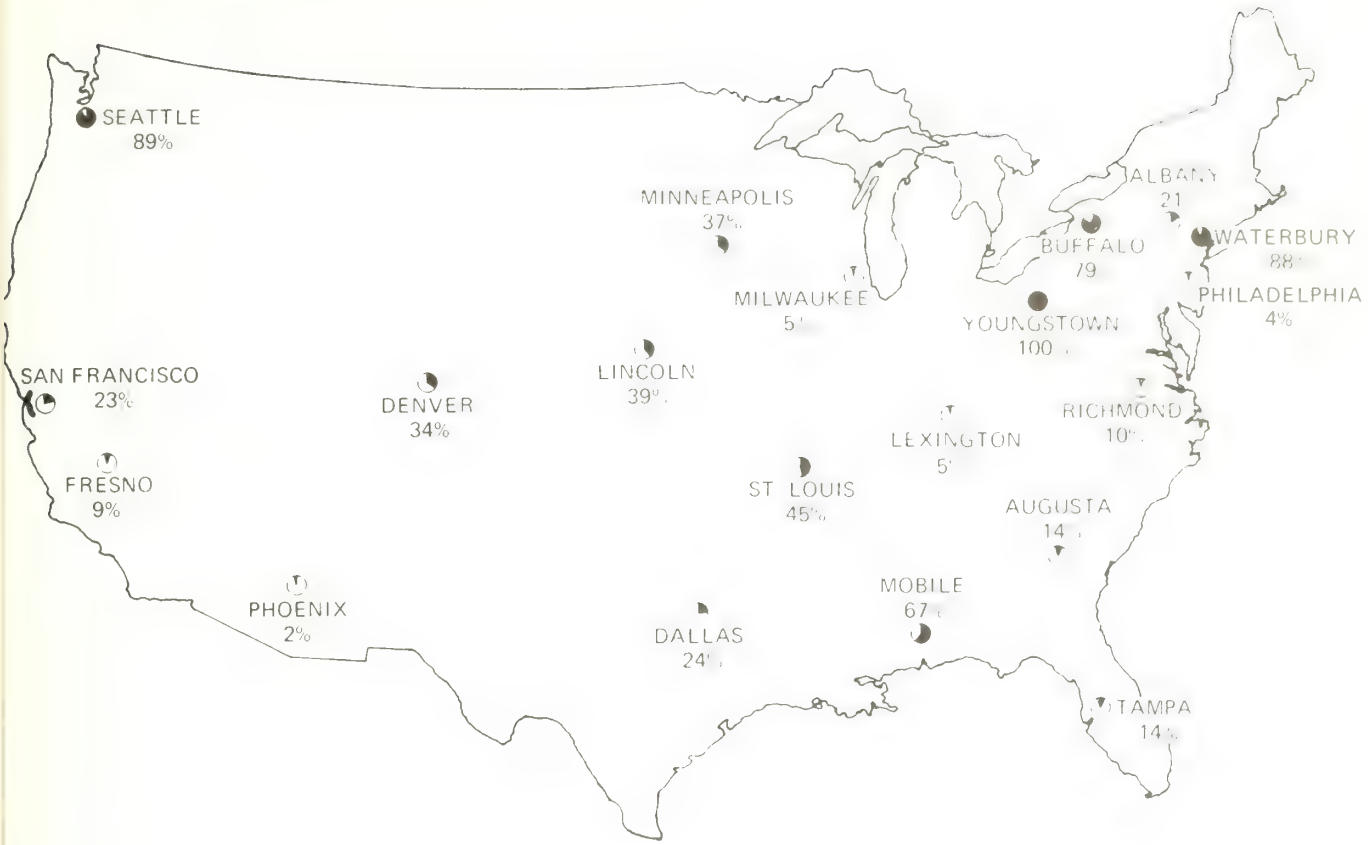

Figure 2.--Wood-based siding share of all siding materials used in sample cities.

Traditional preferences for certain materials in part explain the differences in siding use between cities. Wood shakes are a long-time favorite in New England, stucco is popular in the southwest, and some cities and areas are known as "hard materials" markets where brick and masonry are preferred. These preferences often stem from such technical characteristics of the material as maintenance properties, architectural suitability, or cost.

RANKING OF FACTORS THAT DETERMINE CHOICE OF SIDING

A builder's selection of siding is seldom based on only a single criterion, but rather on a number of considerations--specific criteria or problems that vary among builders and locations (such as the particular performance conditions encountered, or the style of home that is favored). Different builders may consider the same factors highly important but end up using different siding materials. This is shown in the following tabulation:

Factors	Most important	Second most important	Third most important
	(Percent of builders)		
Style and architecture	29	13	2
Home buyers' options and preferences	26	10	10
Price of siding, price of home	23	15	13
Maintenance, performance	9	37	29
Installation, finishing	6	12	9
Availability, supply services	1	4	2
Other	6	6	5

It can be noted that the factors that rate high in importance include some of wood's strongest advantages--style, appearance, and regional preferences--as well as some of its greatest disadvantages--maintenance requirements and performance (particularly dimensional instability).

ARCHITECTURAL STYLE

Siding is a conspicuous part of the house and if a certain architectural effect is desired, siding plays a big part in creating that effect. Two out of three builders in this study indicated that architecture, style, and appearance had some bearing on their choice of siding. For example, among those who built colonial style houses, most (70 percent) used lap-type siding ("bevel," "drop," or "clapboard") to achieve the proper architectural effect. Lap siding, brick, and board and batten sidings predominate in other traditional styles such as "provincial," "plantation," etc. In contemporary houses, all types and patterns are common, but builders frequently select a siding to create a desired effect; for example, board and batten, channel groove, or v-groove lumber, or grooved plywood to carry out vertical lines in a house, or lap siding to create a low profile. Use of two or more sidings is particularly common in contemporary styles.

The style of the house does not necessarily determine which siding material is used, however, because most types and patterns of siding are available in a number of materials that provide a similar architectural effect. For example, lap siding is available in lumber, fiberboard, aluminum, asbestos, vinyl, and several other materials. Therefore, builders can achieve the "proper" type siding using whatever material they or their home buyers prefer. There are exceptions to this, of course, such as the "Spanish villa" style where stucco is considered to be the only "proper" siding.

APPEARANCE

Although similar overall architecture and pattern can be achieved with several siding materials, some builders note differences in the appearance qualities of these materials. About one-third of the builders (mostly smaller builders of high-priced homes) commented favorably on the appearance qualities of some specific sidings. Of these builders,

47 percent cited favorable appearance of lumber
21 percent cited favorable appearance of plywood
18 percent cited favorable appearance of brick
14 percent cited favorable appearance of other materials

Favorable comments on lumber are that it is "authentic," has a quality image, and gives a heavy shadowline on lap siding. Both lumber and plywood with rough-texture surfaces are favored for creating a rustic effect where this is desired in ranch and rustic style houses. Brick also has a "proper" look and quality image, according to builders.

On the other hand, several siding materials were reported to have unfavorable appearance qualities. About one in six builders noted appearance shortcomings of certain sidings, particularly aluminum, fiberboard, and asbestos. Their comments included "low price image," "lack beauty," "tract image," and "not good looking." Nearly all of these builders were located in cities where the materials involved are commonly used.

MAINTENANCE AND PERFORMANCE

Differences in maintenance requirements and other performance characteristics among siding materials contribute to geographic variations in siding use. Furthermore, the builder usually feels that using materials that are as troublefree as possible is necessary to prevent callbacks and to enhance his reputation.

Wood sidings offer some performance advantages, according to builders. In general, wood sidings are considered strong, durable, and resistant to damage. Builders in northern cities noted the good insulating properties of wood. Fiberboard and plywood are considered warpfree and resistant to splitting, and lumber and fiberboard are considered easy to paint by some builders.

On the other hand, wood sidings have some major shortcomings. The most common criticism of builders is that wood sidings require painting (or staining) initially--that subsequent paint maintenance is needed. In the Southwest, extreme heat and dryness result in short paint life (several builders mentioned "no more than 2 years"); this is the main reason for low wood use in that area. In other areas, maintenance problems are not so severe but some paint peeling on lumber and fiberboard, and staining and bleeding on wood shakes were reported.

Instability was another criticism made of wood sidings--checking of plywood surface, warp and shrinking of lumber, and buckling and shrinkage of fiberboard. All detract from the appearance of the siding; shrinkage after the siding is installed, for example, results in unpainted gaps along the edges of sidings such as lap and board and batten.

Comments on maintenance and performance of nonwood sidings were mostly favorable. Aluminum, brick, asbestos, stucco, and vinyl are generally considered maintenance-free. Some builders did however cite shortcomings of aluminum--it "pops" due to expansion when temperature changes, it dents easily from hail, and is difficult to repair if damaged.

Figure 3 gives an overall picture of builders' comments on the maintenance and other performance characteristics of siding materials. The effect of these factors on builders' use of wood varies among individual sidings and by geographic areas, but nonwood sidings are generally favored over wood sidings in terms of maintenance and performance.

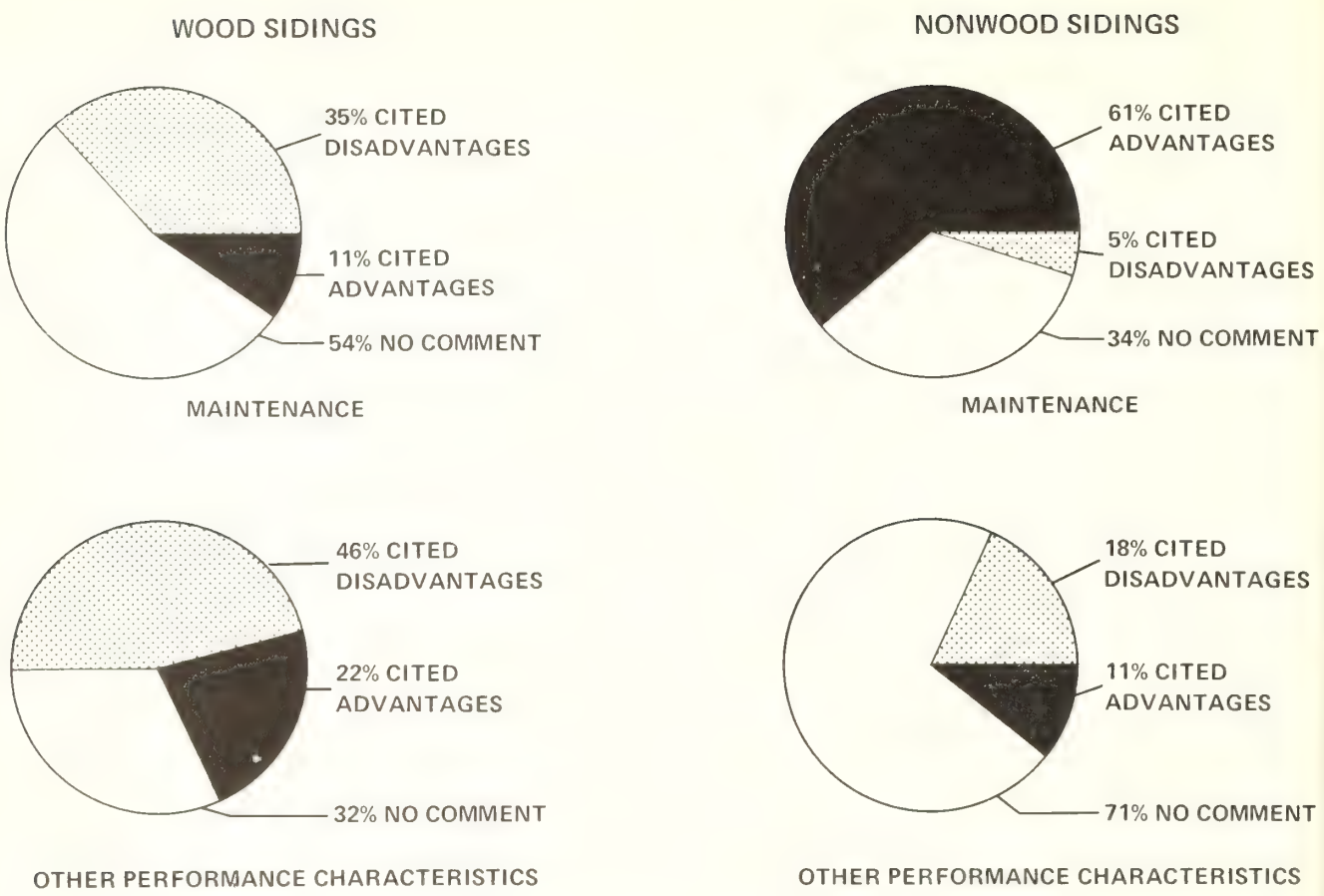

Figure 3. --Builders' comments on maintenance and other performance characteristics, wood and nonwood sidings.

BUYERS' INFLUENCE

Home buyers have a strong influence on builders' choice of siding as a result of their regional preferences for certain materials--shakes in the Northeast, stucco in the Southwest, brick in individual cities. Home buyers were not contacted; therefore, it was not possible to identify firsthand what leads to these preferences. Builders indicate that maintenance, insulation, image, and other factors contribute.

Home buyers also have a direct influence on siding use when they are given options on siding. Among the builders,

29 percent offered a choice of any siding material
28 percent offered a limited choice of siding material
13 percent limited choice of siding to only most expensive homes
30 percent did not offer choices or options on siding.

Many builders indicated, however, that buyers usually ask the builder's advice on which siding he should choose, and frequently select the type shown on model homes. Therefore, the builder has considerable influence even when the buyer has a choice. Some builders also limited the choice of siding to those materials that are similar in cost, or offered other sidings on an "at cost" basis. In addition, several builders limited the buyer's choice to secondary siding (trim or accent panels).

About one-third of the builders used siding as a sales feature of the house. Brick and aluminum were featured as "maintenance-free," fiberboard and lumber as "easy maintenance," and a few builders used guarantees offered by fiberboard manufacturers as a sales point. Appearance of lumber and fiberboard was occasionally used as a sales point. Overall, however, builders indicated that siding is not a major sales feature because buyers more or less take siding for granted, particularly in the case of materials that are common and preferred in the area.

In a few cities, builders reported land developers require that a certain proportion (usually 50 percent or more) of each house be brick sided. Reportedly this is to insure property values through use of a "permanent" good-looking siding and to achieve a look of compatibility and prestige in the development.

COSTS

The installed cost of siding has some effect on siding choice, but it is not the deciding factor in most cases. For example, the installed cost for brick is higher than for other sidings, but the extent to which brick is used even in lower priced homes indicates that local preferences often take precedent over lower cost alternatives. On the other hand, cost appears to weigh heavily in builders' choice of board or sheet type sidings. One of the main reasons builders gave for not using more overlaid siding or vinyl siding is that it costs more than other materials. If a siding costs much more than fiberboard or aluminum, for example, it is competing with brick. Several builders said they would prefer brick to a high-cost sheet or board siding because brick is considered a prestige siding.

Costs vary among individual builders because of differences in grade or quality of materials used and differences in methods of allocating labor cost. Brick siding does cost considerably more in cities in the North than in cities in the South (table 1). Most of this cost difference is because of the wage differential for bricklayers.

Table 1.--Average costs per square foot for purchase installation, and finishing of siding materials[1]

Siding material	Purchase price	Installation	Finishing	Total
	Dollars per square foot			
Aluminum	0.27	0.17	--	0.44
Brick, North[2]	.49	.81	--	1.30
Brick, South[2]	.36	.35	--	.71
Fiberboard	.22	.13	.09	.44
Lumber	.24	.13	.10	.47
Plywood	.20	.13	.11	.44
Stucco[3]	--	--	--	.35

[1]These are averages of 1965 and 1966 costs as reported by builders, based on their records or estimates. No attempt was made to adjust for differences in quality of materials used.

[2]North: Albany, Buffalo, Lincoln, Milwaukee, Philadelphia, Richmond, and St. Louis. South: Augusta, Dallas, Denver, Lexington, and Mobile.

[3]Cost breakdown not available.

INSTALLATION AND FINISHING

Wood sidings are generally considered easy to install. Builders feel wood sidings are easy to cut and fit with conventional tools and do not require special skills. Some other specific advantages reported were: lumber is lightweight and rigid, which makes it easy to handle; fiberboard comes in uniform lengths, which minimizes waste; plywood is easy to install because it comes in large sheets. Several builders (mostly those who build one-story brick or block houses) purchased prefabricated gable end roof trusses with plywood or fiberboard siding already installed, which reportedly reduces labor costs.

Several builders reported some installation problems with lumber: "it splits"; "warp and odd lengths create waste." Only a few builders had used overlaid wood sidings and although these apparently are readily workable (sawing, fitting, etc.) they are reportedly subject to damage during installation. The few comments on installing nonwood sidings included: "aluminum is lightweight to handle but dents easily"; "brick requires skilled labor"; "using aluminum means dealing with a separate applicator crew"; "brick is difficult to work with in cold weather." Comments of builders on siding installation are summarized in figure 4.

Raised grain, flat grain, and other irregularities cause problems when painting lumber and plywood siding. Fiberboard, in contrast, is considered an easy material to paint because of its smooth uniform surface. However, some builders feel that the prepriming on fiberboard is too thin to serve as the primer coat.

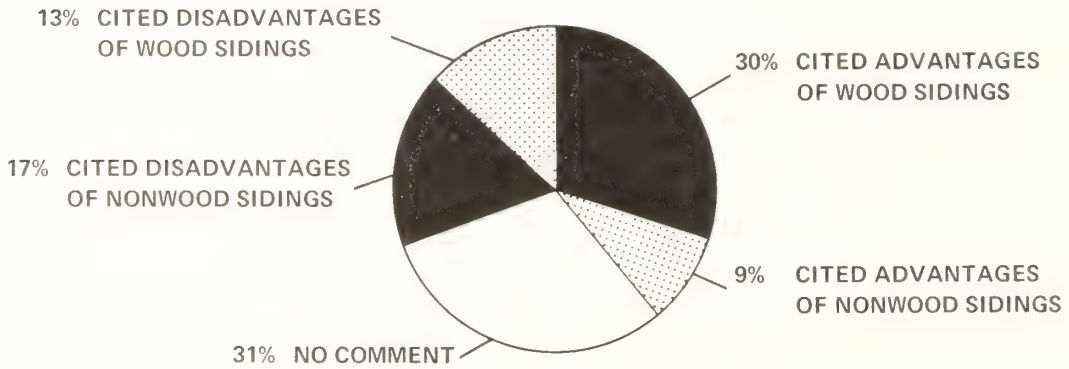
13% CITED DISADVANTAGES OF WOOD SIDINGS
30% CITED ADVANTAGES OF WOOD SIDINGS
17% CITED DISADVANTAGES OF NONWOOD SIDINGS
9% CITED ADVANTAGES OF NONWOOD SIDINGS
31% NO COMMENT

Figure 4.--Builders' comments on installation of siding materials.

AVAILABILITY AND SUPPLY SERVICES

Availability of siding and suppliers' services are not generally considered to be critical factors in the builders' choice of siding. Siding availability is mostly good and suppliers' services are adequate. For many builders, siding is just one part of the overall construction materials package and their choice of suppliers is based on receiving good service on a wide range of building items.

Retail yards are the most common source of wood sidings. Over three-fourths of the builders who use lumber, plywood, or fiberboard purchase these sidings from retailers (table 2). In terms of volume, however, manufacturers and wholesalers are also major suppliers. Retailers are used more often by builders who purchase only small quantities of wood sidings, such as small builders (who build few houses), and builders who use wood siding mostly for such features as accent panels, etc. Wholesalers and applicators are major supply sources for aluminum siding.

Builders use a number of different supply sources for siding, but no substantial differences in suppliers' services (prompt delivery, credit, discounts, etc.) were cited. However, about one-fifth of the builders who used lumber siding noted that it was difficult to obtain. They were mostly builders who used only a small volume of lumber siding and purchased from retailers. About 15 percent of the builders indicated that information on siding is lacking. Mostly their comments pertained to wood sidings: "need more information on buckling of fiberboard," "more information on painting wood needed," "better price and grade information of lumber siding," "wood needs more promotion."

Table 2.--Supply source for selected siding materials, percent of builders, and percent of volume[1]

Supply source	Lumber		Plywood		Fiberboard		Aluminum	
	Builders	Vol.	Builders	Vol.	Builders	Vol.	Builders	Vol.
	Percent							
Retailer	79	41	73	26	82	50	32	9
Wholesaler	3	3	4	20	6	26	32	78
Manufacturer	18	56	9	52	6	21	5	--
Other[2]	--	--	14	2	6	3	31	13

[1]Percent of builders based on number who purchased the siding material from each source. Percent of volume based on how much purchased from each supply source.

[2]"Other" for plywood and fiberboard--prefabricators who supply siding installed on roof truss gable ends; "other" for aluminum--primarily applicators who supply and install the siding.

MARKET OUTLOOK FOR WOOD SIDINGS

The desire on the part of some home buyers for "genuine," "authentic," and "traditional" sidings will probably assure a continuing demand for such siding material as lumber, shake, and brick. Rough-sawn lumber and plywood sidings have become highly popular in some cities because of their rustic effect. These esthetic requirements of some builders and home buyers can probably be met only by "real" wood sidings.

On the other hand, a large segment of the siding market is not strongly committed to any one material. Although the general trend toward more expensive homes is currently encouraging the use of "authentic" sidings such as lumber and brick, builders comments on what sidings they expect to use in the future indicate an interest in new siding materials that solve problems of performance and maintenance and reduce costs. Several builders who recently changed to aluminum siding said they made this change because of the buyer's request. Apparently advertising aimed at the home buyer has been successful in promoting aluminum.

It seems likely that all competing sidings will have to measure up to a certain minimum level for all criteria including cost, maintenance, suitable appearance, and workability. Among several nonmasonry sidings, total installed costs differ by only a few cents per square foot. This permits greater influence of noncost factors on choice of siding even if the builder has fairly rigid cost objectives or limitation. It is notable also that vinyl and overlaid wood sidings are not widely used as yet, apparently because of higher installation costs, even though they have other favorable characteristics.

It appears then that some improvements in wood sidings must be made if these are to remain competitive, particularly if certain disadvantages of competing sidings are to be overcome. Improvements needed in wood sidings include: reducing maintenance, improving stability (warping and checking), providing more technical and promotional information, and preventing periodic shortages at the builder level.

Benson, Robert E.

1968. Factors that affect use of wood siding materials in single-family homes. U.S. Dep. Agr., Forest Serv., Intermountain Forest and Range Exp. Sta., Ogden, Utah 84401. 10 pp., illus. (U.S.D.A. Forest Serv. Res. Pap. INT-57)

A survey of builders in 20 cities throughout the Nation shows preferences for siding materials vary regionally. Wood-based sidings are favored for appearance and workability, but are more difficult to maintain than are several other leading nonwood siding materials. The market outlook for wood sidings depends partly on improving maintenance and other performance properties and partly upon the continuing esthetic appeal of wood to home buyers.

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EFFECTS OF THINNING AND FERTILIZING ON PRODUCTION OF WESTERN WHITE PINE SEED

BURTON V. BARNES

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Intermountain Forest & Range
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Ogden, Utah

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COVER PHOTO

Cathedral Peak
seed production area,
Coeur d'Alene National
Forest, after thinning.

USDA Forest Service
Research Paper INT-58
1969

EFFECTS OF THINNING AND FERTILIZING ON PRODUCTION OF WESTERN WHITE PINE SEED

Burton V. Barnes

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
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EFFECTS OF THINNING AND FERTILIZING ON PRODUCTION OF WESTERN WHITE PINE SEED

Burton V. Barnes

INTRODUCTION

Artificial regeneration has increased markedly during recent years. Between 1950 and 1960 the number of acres planted annually in the United States by all agencies increased from about 500,000 to 2,100,000. Subsequently, planting declined but has apparently leveled off at about 1,300,000 acres per year (31).[1] To provide enough nursery stock for this tempo of planting, production of seed of good genetic quality needs to be increased and stabilized.

Seed production areas and seed orchards have been established to fill this need. A seed production area is typically a stand of desirable trees set aside for seed production and usually given special cultural treatments to increase seed production. In contrast, a seed orchard is a plantation of trees (established by grafting or from cuttings or seedlings) that have been rigorously selected and have been or are being tested to determine their genetic worth. Typically, seed production areas provide a temporary source of seed until seed orchards come into production and provide markedly improved seed. The number of seed production areas is increasing rapidly--already 10,068 acres are now devoted to this use in the United States (31).

In 1959 the Northern Region of the U.S. Forest Service (Region 1) established a western white pine seed production area near Cathedral Peak in Coeur d'Alene National Forest to provide good quality seed from a highly regarded source. Experiments were begun in this area to determine the effects of thinning and fertilizing upon tree, cone, and seed traits as well as on growth (24).

BACKGROUND

Literature describing the establishment and management of seed production areas has been summarized by Rudolf (22, 23) and Zobel et al. (33). A general review of factors affecting seed production, including insect and disease problems, was published by Hoekstra et al. (13); and Matthews (16) published an excellent review of seed production. A brief review of the differentiation of floral primordia and the effects of thinning and fertilizing upon strobilus and cone production[2] of fruiting-age trees is pertinent to the results presented.

The stage of physiological development of a tree and the time of differentiation of floral buds are two of the most important factors affecting cone production. It is well known that juvenile trees typically do not flower, whereas those in the adult stage are physiologically capable of flowering. In this paper we are concerned only with trees in the adult stage and with the factors that stimulate primordium and cone production.

The time of visual recognition (microscopic and macroscopic) of floral primordia in the soft pines is later than in the hard pines. Present evidence indicates that hard pines are typically more advanced in primordium development at any given time than

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[1] Numbers in parentheses refer to items in Literature Cited.

[2] To distinguish between two arbitrary developmental stages of the female reproductive organ in this paper, the term strobilus is used to designate this structure as the newly formed organ, while the overwintering form and all stages thereafter are termed cone.

soft pines; thus it is not unreasonable to expect that the beginning of differentiation of floral structures may be earlier.

Male and female strobili of ponderosa pine and Austrian pine are detectable by eye in September. Mergen and Koerting (17) reported that male and female floral primordia of slash pine were recognizable by mid-July and late August, respectively, of the year before flowering. However, floral primordia of soft pines are not as easily detectable.

In repeated histological work with eastern white pine, Ferguson (8) was never able to find male strobili in the fall. They were visible only by late April or early May of the year of flowering. She found female strobili visible (histologically) only in late April or early May.

Owston (19) found no reproductive primordia in fall and winter buds of young eastern white pine even though female cones were present on some study trees.[3] He believed this was due to lack of visible differentiation until the following spring. Although the same might be true for male strobili, Owston's trees produced negligible numbers of male cones, and failure to identify them could well have been due to their absence from the samples. Owston found the developmental cycle in southeastern Michigan such that male primordia might be differentiated, but not necessarily visible, in early July. Female cones might be differentiated toward the end of August, but would not look any different than vegetative primordia until the following spring.

Stephens (28) found fully differentiated male strobili in mid-November collections of terminal buds from four eastern white pine trees, but not in late August collections. However, he did not report finding male strobili in all trees; hence it is possible that considerable variation might exist among individual trees. Although differentiation of female primordia "may possibly occur the season prior to flowering," the "actual development of the strobili does not occur until resumption of growth by the bud in early spring," Stephens said.

Konar and Ramchandani (14) working with Pinus wallichiana Jacks. (=P. griffithii McClelland) reported that male strobili were "initiated" from the middle of October to the beginning of November and female strobili were "initiated" in February. In short, evidence indicates that in the soft pines, (a) male primordia are differentiated and microscopically visible before female primordia and (b) that male primordia are microscopically visible in late fall, but for female primordia differentiation occurs in the spring of the following year.

Generally, the release of seed trees increases production of strobili and cones; cone production is inversely proportional to stand density (1, 5, 6, 10, 20, 32). Florence and McWilliam (9) found that the stand density that maximizes cone production per tree is much lower than one giving maximum production per acre. For young slash pine, the density for optimum production was approximately 120 trees per acre. Pollen production closely followed the trends in cone production. Allen and Trousdell (1) found that release significantly increased the proportion of sound seed of loblolly pine; Reukema (21) observed no increase in sound seed following thinning of Douglas-fir stands. In years of generally light strobilus formation, release apparently has little effect on strobilus production (20, 21).

Fertilizing is definitely known to stimulate cone and seed production in numerous forest species, but results are too varied to permit a definite prescription (16). The amount of response depends greatly upon the genetically determined ability to flower, kind and time of treatment, and conditions of the environment. Steinbrenner

[3]Also personal communication from P. W. Owston, July 2, 1968.

et al. [27] found that a combined application of nitrogen and [illegible] increased cone length and seed weight in Douglas-fir. The highest treatment levels of both fertilizers caused the greatest increase in seed weight. Mergen and Voight (18) reported that fertilizer treatments produced heavier slash pine seeds. However, in one previous experiment with western white pine, fertilizer was ineffective in stimulating strobilus production of fruiting-age trees (2).

Much less is known about fruiting response related to time of differentiation of flower buds and timing of cultural treatments. Applying fertilizer to precede or coincide with differentiation of flower buds may markedly increase cone production (30). Owston's investigations of eastern white pine in Michigan indicated that application of fertilizer in August could influence existing primordia that have the potential for becoming male cones and could possibly affect both the number and condition of the primordia that have a female potential.[4] Since floral primordia could abort, presumably at any time between differentiation and anthesis, improving nutrition (through fertilizing) or increasing moisture availability (through thinning) any time after initiation could reduce abortion and thus increase the number of strobili available for pollination and subsequent development. Some evidence of reduction of abortion is available (27).

Insects may cause serious losses to cone crops of both eastern and western white pine (3, 12). Larvae of the cone beetle, Conophthorus monticolae Hopkins, and larvae of the cone moths, Eucosma rescissoriana Heinrich and Dioryctria abietella (D.&S.), may destroy or severely damage western white pine cones.

ESTABLISHMENT OF THE SEED PRODUCTION AREA AND EXPERIMENTAL DESIGN

Personnel from the Intermountain Forest and Range Experiment Station and the National Forest System cooperated in selecting the site of the seed production area. Some of the criteria for selection of the site were: presence of young, high quality trees in natural stands or plantations; trees in plantation from a known source; presence of cones on trees; accessibility of site in spring and fall; flatness of terrain; absence of debris and brush; proximity to water; and homogeneity of soil. Meeting all these requirements was difficult. The site selected from 15 alternatives on the Coeur d'Alene National Forest was a young plantation that was producing exceptionally large numbers of cones, and it was located on relatively level terrain. The growth of this stand exceeded that of natural western white pine stands of comparable age (4). Some disadvantages were its relative inaccessibility, lack of water, and lack of exact information about the provenance of the planted stock it originated from.

In September 1959, two areas (Units 1 and 2), each approximately 3 acres and located about 1 mile apart, were selected in a 40-year-old plantation near Cathedral Peak, Coeur d'Alene National Forest, Shoshone County, Idaho. Later that fall, each unit was subdivided and thinned. One subunit was thinned to a spacing of approximately 30 by 30 feet (48 trees per acre) and the other to 20 by 20 feet (109 trees per acre). Before thinning, the spacing was approximately 9 by 9 feet (538 trees per acre).

Seed trees were selected on the basis of freedom from lethal blister rust cankers, spacing, fruitfulness, form, and vigor. When the area was thinned, a small amount of slash was chipped. The remainder of the slash was chipped in June and July 1960, and left in piles. Tree boles too large to chip were piled within the area. Trees were pruned to about 8 feet, and 14-inch aluminum bands were attached to all trees to prevent squirrels from cutting the cones. The total cost for establishment of the area, excluding overhead and research costs, was about $1,000 per acre. Because of the high cost of thinning, chipping, and clearing, isolation strips were not provided.

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[4] Ibid.

In June 1960, three circular 1/10-acre sample plots were established in each subunit and three in the unthinned plantation surrounding each unit. Thus, nine sample plots were established in or near each of the two units.

Thinning did not produce the planned number of trees per acre on the sample plots. Angle summation (25) and counts of number of trees per 1/10-acre plot in 1962 indicated that the actual average spacing on the six thinned sample plots in Unit 1 was similar: 87 and 84 trees per acre for the 20-foot and 30-foot spacings, respectively. In Unit 2, spacings of the thinned stands were substantially different: 93 trees per acre for the 20-foot spacing and 60 trees per acre for the 30-foot spacing. Combined data for both units indicated the difference in density (angle summation data) between the 20-foot and 30-foot spacings was not significant ($P>.10$). In analysis of data for the three levels of spacing, the most significant results were the differences between thinned and unthinned stands.

In each level of spacing, two of the three plots were fertilized in August 1960 and 1961 to coincide with early-fall precipitation. Fertilizer treatments were assigned at random. One plot received approximately 300 pounds per acre each of nitrogen (N), phosphorus pentoxide (P_2O_5), potassium oxide (K_2O) in a 13-13-13 commercial fertilizer.[5] The per-acre application rates for elemental nitrogen, phosphorus, and potassium were approximately 312, 136, and 259 pounds, respectively. This treatment was designated NPK. The other fertilized plot received approximately 300 pounds per acre of elemental nitrogen in the form of ammonium nitrate (NH_4NO_3). The third plot was untreated.

The three dominant trees nearest to plot center were selected as sample trees for counts of male and female strobili and for cone collections. Additional cone collections were made in the next three dominant trees closest to plot center.

In late June or early July of 1960, 1961, and 1962, each of the three sample trees nearest to plot center was climbed, and the male and female strobili were counted. Each year the numbers of strobili and cones were recorded for all branches in whorls originating from 1954 through 1957; some strobili and cones were counted on whorls 1955 to 1958. An analysis of variance of 1961 strobilus production data indicated between-tree variance was approximately twice that of between-whorl variance. Consequently in 1962, strobilus and cone counts were made on six sample trees instead of three. The strobilus count of 1 year was checked and corrected by the cone count of the following spring.

In late August or early September of 1960, 1961, and 1962, cones were counted and collected from the six sample trees. Climbers were instructed to collect six uninfested cones from the sample whorls. The number of cones and their condition (infested or uninfested) on the sample whorls were recorded at that time. In the unthinned plots, cones were covered by cloth bags before collection to prevent squirrel cutting.

The cones from each sample tree were spread out to dry in a greenhouse. Seeds were extracted with extreme care and cone lengths were measured. Seeds were dewinged and winnowed, and hollow and sound seeds were counted; sound seeds were weighed.

Despite precautions, some infested cones were collected. In 1961 and 1962, insect attack was so heavy that infested cones had to be collected from some trees. Seed from infested cones was extracted separately.

Branches for male strobilus counts were chosen at midcrown in the center of the male-flowering portion of each sample tree. One branch was selected on the north side and one on the south side of the tree. Male strobilus clusters were counted on these

[5]Fertilizer was supplied by Cominco Products Inc., Spokane, Washington.

branches of each of the three sample trees. The number of strobili per cluster was determined by sampling and the total number of strobili for each branch was estimated (number of clusters X average strobili per cluster).

Analysis of variance was used to determine the effects of spacing and fertilizing upon the following variables: female strobilus production, male strobilus production, percentage of hollow seed, seed weight, cone length, number of seed per centimeter of cone length, seed production per tree, and seed production per acre.

RESULTS

Female Strobilus Production

Strobilus production increased in response to thinning (table 1). The difference between the thinned and unthinned stands was significant ($P<.05$) in 1960 and highly significant ($P<.01$) in 1961 and 1962. Strobilus production per whorl in the 30- by 30-foot spacing was significantly greater than that in the 20- by 20-foot spacing in 1960 ($P<.06$) and 1962 ($P<.025$).

Response to fertilizing was less marked, but strobilus production increased significantly in the fertilized plots in 1961 ($P<.05$). This was the first year fertilizer could have been effective because it was not applied until the fall of 1960. In 1962, strobilus production in the fertilized plots was 33 percent greater than in unfertilized plots, but this difference was not significant ($P>.10$). Nitrogen alone increased strobilus production as much as did the complete fertilizer. Fertilizing brought about a deep, blue-green needle color and increased needle length. The deep, bluish-green color was more striking in NPK plots than in nitrogen-only plots.

Table 1.--Average female strobilus production per whorl before and after thinning (1959) and fertilizing (1960 and 1961), Units 1 and 2 combined[1]

Year	Spacing (ignoring fertilizer)			Fertilizer (ignoring spacing)		
	Unthinned	20'	30'	Unfertilized	N	NPK
	Number of strobili					
1959[2]	4.2	4.3	5.6	4.3	4.5	5.3
		---Thinned---				
1960	1.5	2.3	3.9	2.9	3.0	1.8
					--Fertilized--	
1961	2.1	7.1	8.5	3.6	7.0	7.1
					--Fertilized--	
1962	1.4	3.7	5.9	3.0	4.3	3.7

[1]Averages based upon strobilus counts for four whorls in each of three trees per 1/10-acre plot. The data for 1962 are based upon counts in six trees per plot.

[2]The number of female cones counted in the spring of 1960 was used to estimate production of 1959 female strobili before thinning and fertilizing.

Male Strobilus Production

Production of male strobili was significantly greater ($P<.025$) in the spring of 1960 on the trees released by thinning in October 1959 than on trees in the unthinned stand (table 2). Male strobilus production was also greater in the fertilized plots in 1961 and 1962 than on unfertilized plots, but the difference was not significant either year ($P>.10$). Strobilus production in 1962 was light and erratic.

Cone Length

Thinning caused a marked reduction in cone length (table 3). In 1960 no effect of treatment was noted. In 1961 the cones in unthinned plots were significantly longer than those in thinned plots ($P<.025$) and cones in plots with 20-foot spacing were significantly longer than those in plots with 30-foot spacing ($P<.05$). In 1962, cones in the unthinned plots were again significantly longer ($P<.07$) than cones in thinned plots.

Cones in fertilized plots were significantly longer than those in unfertilized plots in 1961 and 1962 ($P<.005$). In 1961 cones in plots receiving complete fertilizer were significantly longer ($P<.05$) than cones in plots receiving nitrogen only.

Sound Seed Per Centimeter of Cone Length

The effect of thinning and fertilizing upon the number of sound seed per centimeter of cone length was negligible.

Table 2.--Average production of male strobili per sample branch after thinning (1959) and fertilizing (1960 and 1961), Units 1 and 2 combined[1]

Year	Spacing (ignoring fertilizer)			Fertilizer (ignoring spacing)		
	Unthinned	20'	30'	Unfertilized	N	NPK
	Number of strobili					
		--Thinned--				
1960	140	303	363	265	305	236
					--Fertilized--	
1961	409	500	345	379	458	416
					--Fertilized--	
1962	119	62	76	8	102	146

[1]Average based on estimates of strobili on each of two branches on three trees per plot.

Table 3.--Average cone length (cm.) after thinning (1959) and fertilizing (1960 and 1961), Units 1 and 2 combined[1]

Year	Spacing (ignoring fertilizer)			Fertilizer (ignoring spacing)		
	Unthinned	20'	30'	Unfertilized	N	NPK
		--Thinned--				
1960	17.4	17.0	16.5	16.7	16.8	17.4
					--Fertilized--	
1961	18.0	17.2	16.2	15.8	17.2	18.3
					--Fertilized--	
1962	18.0	17.3	17.1	15.8	18.1	18.4

[1]Average cone length based on an average of six cones per tree, six trees per plot in 1960; five cones per tree, four trees per plot in 1961; and five cones per tree, six trees per plot in 1962.

Percentage of Hollow Seed

In all but one instance no significant difference in percentage of hollow seed was found for the treatments during the 3 years of seed collection. The only exception was in 1962 when treatment with complete fertilizer resulted in a significantly lower percentage of hollow seed ($P<.005$) than did treatment with nitrogen. Apparently there is sufficient pollen in the thinned area to maintain adequate production of sound seed on individual trees.

Seed Weight

Spacing had less effect on seed weight than did fertilizing (table 4). In 1961 and 1962 the seed weight in plots with 30-foot spacing was less than that in either the unthinned plots or those with 20-foot spacing. In 1961, the difference in seed weight between plots with 20- and 30-foot spacing was significant ($P<.07$).

Seed weight in fertilized plots was significantly greater ($P<.005$) than in the unfertilized plots in 1961 and 1962. Seed weight was 5 percent greater after treatment with complete fertilizer than after treatment with nitrogen in 1961 and 1962, but the difference was not significant ($P>.10$).

No significant difference ($P>.10$) was found in the weight of seed from infested and uninfested cones regardless of treatment.

Table 4.--Average weight per seed (mg.) after thinning (1959) and fertilizing (1960 and 1961), Units 1 and 2 combined[1]

Year	Spacing (ignoring fertilizer)			Fertilizer (ignoring spacing)		
	Unthinned	20'	30'	Unfertilized	N	NPK
		--Thinned--				
1960	16.2	16.2	16.2	16.0	16.7	15.8
					--Fertilized--	
1961	20.2	21.9	19.1	17.5	21.4	22.3
					--Fertilized--	
1962	18.5	18.3	18.0	16.4	18.7	19.8

[1]Averages based on seed collected from an average of six trees per plot, six cones per tree in 1960; four trees per plot, four cones per tree in 1961; and six trees per plot, five cones per tree in 1962.

Seed Production Per Tree

Data for production of female strobili, cone length, and average number of seed per centimeter of cone length were used to compute seed production per tree (table 5). To compute total strobilus production per tree, strobilus production based on the four-whorl sample was doubled. This adjustment was determined by complete counts of strobili on 24 trees that were topped in 1961 and on a second group of 12 trees (untreated sample trees in plots in the thinned stand). The total count for both groups was almost exactly twice the number of strobili in the four-whorl sample.

To account for overwinter loss, i.e., the difference between number of strobili produced and the number developing into mature cones the following spring, 10 percent was deducted from the total strobilus production per tree for each plot. This deduction was based upon a loss in strobili from June 1960 to June 1961, and from June 1961 to June 1962 of 11 percent and 8 percent, respectively.

Thinning significantly increased per-tree seed production in 1960 ($P<.025$), 1961 ($P<.005$), and 1962 ($P<.005$). Seed production in plots with 30-foot spacing was significantly greater in 1960 and 1962 than in plots with 20-foot spacing ($P<.08$ and $P<.05$, respectively).

Use of fertilizer significantly increased production per tree in 1961 ($P<.06$) and 1962 ($P<.05$). No significant difference was found between treatments with nitrogen and treatments with complete fertilizer.

Table 5.--Seeds produced per tree after thinning (1959) and fertilizing (1960 and 1961), Units 1 and 2 combined

Year	Spacing (ignoring fertilizer)			Fertilizer (ignoring spacing)		
	Unthinned	20'	30'	Unfertilized	N	NPK
		--Thinned--				
1960	8,143	13,540	21,128	16,095	16,533	10,183
					--Fertilized--	
1961	12,549	48,244	53,316	20,876	46,122	47,111
					--Fertilized--	
1962	8,833	25,562	37,638	17,580	27,631	26,822

Seed Production Per Acre

The seed production per acre was computed by multiplying the number of seed per tree by the actual number of trees per acre (table 6). The number of trees per acre was determined not by simply computing the theoretical number per acre for 9-foot, 20-foot, and 30-foot spacings, but by counting the trees in each plot. For the unthinned plots the number of trees was arbitrarily reduced by one-third before computing seed production per acre. This was done to account for intermediate and suppressed trees that would not produce as many cones as the average in unthinned sample plots. This reduction is thought to give a conservative estimate of seed production in the unthinned stand.

In 1960, the seed production in the unthinned plots was significantly greater than that in the thinned plots ($P<.07$). In 1961 and 1962, the difference between seed production in unthinned and thinned plots was not significant ($P>.10$), although the production in unthinned plots was greater in both years.

Use of fertilizer significantly increased seed production per acre in 1961 ($P<.05$) but not in 1962 ($P>.10$).

Table 6.--Seed production per acre after thinning (1959) and fertilizing (1960 and 1961), Units 1 and 2 combined

Year	Spacing (ignoring fertilizer)			Fertilizer (ignoring spacing)		
	Unthinned	20'	30'	Unfertilized	N	NPK
	Thousands of seed					
		--Thinned--				
1960	2,912	1,212	1,604	2,137	2,265	1,326
					--Fertilized--	
1961	4,503	4,194	3,652	2,613	4,873	4,863
					--Fertilized--	
1962	3,182	2,250	2,794	2,399	3,187	2,640

Infestation by Cone Insects

The number of cones infested with larvae of cone moths (primarily Eucosma rescissoriana Heinrich) was estimated in 1960, 1961, and 1962 (table 7). The thinned plots consistently showed greater loss than the unthinned plots. In 1961, the loss in seed production in Unit 1 was serious, but in Unit 2 it was catastrophic: of the 32 trees bearing cones in the spring in the six plots in the thinned stand of Unit 2, only four trees bore uninfested cones in the fall. Only 3 percent of the total cones borne in spring by these 32 trees was uninfested when cones were collected in late August. Although cone insects do not ordinarily destroy the entire cone (3), the damage is serious. In 1961 and 1962, damage was great enough to preclude cone collection throughout the thinned stand. In 1962, insect activity was apparently somewhat greater in the adjacent unthinned area than it had been in previous years.

Genetic Gain

At most, little genetic gain in growth rate can be expected among trees reared from seed collected in the Cathedral Peak Seed Production Area. The selection intensity (only about 15 percent), method of selection, and heritability preclude achievement of more than minimal gain for any given trait, such as growth rate.

Seed trees were selected for the following characteristics in descending order of importance: freedom from blister rust, spacing, seed production, freedom from recurrent forking, good vigor, long crowns, and fine branching. Seed trees were chosen for several characters that probably have no significant correlation with growth rate. Consequently the growth rate of selected trees may not be significantly different from the mean of the whole population. Also, as Lush (15) demonstrated, the gain for any one character rapidly diminishes as the number of uncorrelated traits selected increases. A low heritability for growth traits apparently operates in juvenile western white pine, according to Squillace et al. (26) and Hanover and Barnes (11). This also would act to reduce the potential gain.

Table 7.--Estimated percentages of cones infested by insects in sample trees, Units 1 and 2 combined

Year	Spacing		
	Unthinned	20'	30'
1960[1]	10.0	15.0	32.2
1961[2]	11.8	56.4	65.8
1962[3]	22.0	69.7	79.2

[1]Estimates based on fall examinations of all cones counted in sample trees in the spring of 1960. Besides visibly infested cones, missing cones and cones that squirrels had cut were presumed infested.

[2]Estimates based on the number of cones infested out of the six best cones collected from each tree. This estimate is conservative since it does not consider many trees where collections were not made because all cones were infested.

[3]In thinned areas, estimates were based on fall examination of all cones counted in sample trees in the spring of 1962. In the unthinned plots, only cones on the tree at time of the fall examination formed the basis of the estimate, but many of them had been cut by squirrels.

Finally, no isolation strip was provided. The thinned areas were completely surrounded by unselected trees, and abundant exchange of pollen is highly probable.

DISCUSSION

The most interesting result was the significant increase (approximately 14 percent) in production of male strobili that occurred in the spring following heavy thinning in early October. This is apparently no anomaly since observations in thinned and unthinned portions of the stand confirmed the counts of strobili. It is reasonable to suppose that the thinnings acted to produce a more favorable physiological condition for (a) differentiation of strobili if this occurred after thinning and/or (b) preventing abortion of strobili if thinning occurred after differentiation of flowerbuds. Until further information is available on the differentiation of flowerbuds of western white pine, it would seem that either or both of these possibilities may explain the findings.

Considerable abortion of female flower buds is known to occur in the spring before pollination,[6] and this also is probably true for male flower buds. Thus, a working hypothesis is that abortion is a constant process that starts soon after differentiation of floral initials and continues after pollination. Abortion may be directly affected by the physiological condition of the shoot and subject indirectly to cultural treatments that alter this condition.

Applications of fertilizer late in the summer of 1960 resulted in a 96-percent increase in production of female strobili in 1961. Whether more buds were differentiated or less abortion occurred after differentiation was completed is unknown. Stephens (29) had similar results in an eastern white pine stand in Connecticut. He found that applying fertilizer in late July stimulated strobilus production the following year, but that treatment in early April the following year failed. The difference of approximately 1 month in time of summer application of fertilizer between

[6]Personal communication, R. T. Bingham, Intermountain Forest and Range Experiment Station, July 10, 1967.

the Idaho and Connecticut experiments probably is not important. In northern Idaho, summers are hot and exceedingly dry. Therefore, applications were made to coincide with the first early fall precipitation, which typically occurs in late August or early September. It would have been important to fertilize earlier if the summer season had been relatively wet.

As was observed in 1960, the technique for sampling male strobili was adequate to register only major changes in production. Apparently neither thinning nor fertilizing modified the large year-to-year differences.

The practical significance of this study is now essentially academic since unimproved stock of western white pine is not planted at present in the Rocky Mountains because of inability to protect this species from white pine blister rust (7). However, several comments are appropriate since similar conditions may exist for other species in this region and elsewhere.

Use of fertilizer significantly increased seed weight--some 21 percent. Two benefits from sowing heavier seeds--better germination and production of more vigorous seedlings--may be very important in nursery operations and regeneration. Mergen and Voight (18) concluded that the advantages of producing larger seeds sufficiently justified the cost of applying fertilizer.

Conventional seed production areas may be neither necessary nor economically justifiable in the future. Preparation of such areas and thinning of stands are expensive. Genetic gain for species propagated from seed collected from such areas is probably negligible. Moreover, such areas are subject to increased incidence of attack by destructive insects. Apparently an unthinned but fertilized stand would be as productive as a thinned, fertilized stand, and would be markedly safer from infestation until efficient, safe, economical measures for insect control are available. A light thinning, to remove suppressed and intermediate trees that typically do not flower, might further increase productivity without starting a sharp increase in insect attack.

Under the conditions stated above, the unthinned stand produced as much good seed per acre as the thinned stand. This conclusion must remain tentative because it is not known definitely that the number of trees per acre in the unthinned area, reduced by one-third, will actually produce the same average number of strobili per tree as trees in the sample plots. However, in the stands observed, a reduction of one-third seemed reasonable.

Seed production per tree may be more important than seed production per acre where the selected trees respond well to cultural treatments, where there is enough pollen, and where insect control can be guaranteed. Costs of seed collection would be lower if cones were concentrated in a few trees rather than scattered over many. However, if collecting by hand is difficult and hazardous, and if cones can be obtained from squirrel caches, fertilized stands that are unthinned or lightly thinned may prove to be more desirable economically and may produce as satisfactorily in both quantity and quality of seed as drastically thinned and otherwise more highly cultured stands.

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In a 40-year-old western white pine plantation developed as a seed production area, heavy thinning and application of fertilizer in the fall significantly increased strobilus production the following spring. Applying fertilizer increased seed weight and cone length significantly, but thinning did not. Insects severely damaged the cone crop in the thinned stand. This study indicates that abundant seed crops, relatively free from insect damage, may be produced without expensive thinning and area preparation operations.

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1969. Effects of thinning and fertilizing on production of western white pine seed. U.S. Dep. Agr., Forest Serv., Intermountain Forest and Range Exp. Sta., Ogden, Utah 84401. 14 pp., illus. (USDA Forest Serv. Res. Pap. INT-58)

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USDA Forest Service
Research Paper INT-59
1969

SELECTING CRAWLER SKIDDERS BY COMPARING RELATIVE OPERATING COSTS

Paul L. Schillings

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PREFACE

A preliminary draft of this report was distributed among 50 representatives of the logging industry in the Northern Rocky Mountain and Southeastern States. They were asked to compare known skidding costs with costs estimated by using the charts in this report. Thirty-six responded that they considered their comparisons to be either "reasonable," "useful," or "worthwhile." No negative replies were received; in fact, 30 of the respondents requested similar information for larger tractors. (See Research Paper INT-60 titled "A Technique for Comparing the Costs of Skidding Methods.") This encouraging response was a motivating factor in our decision to publish this report.

However, the author recognizes that wage increases, material changes, and effects of other economic considerations, such as inflation, have occurred since the data for this report were collected. Therefore, the values shown in the six charts (figures 1-6) probably will have to be adjusted to reflect these increases--in some cases, by as much as 12 percent. If a contractor has not kept cost records, it is recommended that he increase the skidding costs found in the charts by at least 10 percent. If he has maintained a cost accounting system and knows his crawler skidding costs, they may be compared with costs selected from the charts provided operating conditions are similar. After a few trial comparisons, the amounts to adjust chart costs may be made on an individual basis with the preceding remarks as a guide.

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INTRODUCTION

This report is separated into three major sections: (1) working charts, which enable a user to estimate crawler skidding costs per thousand board feet ($/MBF) whenever it is possible to judge skidding distance, terrain type, slope, and operator efficiency; (2) individual graphs giving comparisons and break-even points for various crawler sizes, crew combinations, and operating conditions; and (3) an appendix, which describes how data were gathered and converted to chart presentation.

Data were gathered in the Gallatin, Helena, and Beaverhead National Forests; therefore, the cost estimates should be most accurate for operations in the Northern Rocky Mountain area. This is not to imply that the estimates cannot be used for operations in other areas. Regardless of the area, the following restrictions will hold:

1. Volumes per logs should run from 60 to 140 board feet.

2. Log lengths should be 40 feet or less.

3. The crawler tractors used should fall within the limits of 25 to 80 drawbar horsepower (DBHP).

4. A skidder operator should set his own chokers, or one choker setter should set them for him.

HOW TO USE SKIDDING COST CHARTS

Figures 1 through 6 are the working charts. Basically they are similar; skidding costs are found by following the same procedures on each. A user must select the chart to use by matching crawler classes and crew situations to those of his operations.

To enter any chart he has selected the user must know:

1. The approximate distance in feet from the deck to the general area where logs are hooked. This distance may be paced. After a few "walks" it is surprising how accuracy increases. Be sure to estimate the true skidding distance and not the line-of-sight distance. When the distance changes about 100 feet to a different general area, a new distance should be measured. At the end of a day, week, or other time period, an average is taken of the $/MBF altered by changes in skidding distances. The averaged cost is used over the particular time period observed.

2. The type of terrain in which the crawler must operate. At the top of each chart is a key showing three terrain classifications. In the first graph of each chart, terrain classes 2 and 3 overlap. The right border of the class 2 wedge runs down the middle of the class 3 wedge, and the left border of the class 3 wedge runs down the center of the class 2 wedge. Use of the terrain classifications will be explained in an example later. As terrain classes change, costs are averaged to get a final $/MBF (see requirement 1 above).

3. The average slope in percent over the skidding path. A slope key is shown directly under the terrain key on each chart. The bold vertical lines in the slope key designate a typical section of the terrain wedges shown in the top graph of each chart. If the slope is judged to be 15 percent or less, a point on the left border of the wedge is chosen; if 22 percent, a point in the center of the wedge is chosen; and if 30 percent or greater, a point on the right border of the wedge is chosen. Should the slope fall within the range of 16 to 29 percent, an interpolation is made inside the wedge. The percent of slope may be found with the help of an inexpensive clinometer, or it simply can be estimated. When a slope is negative, that is, going downhill to the viewer, the minus sign is disregarded; only the absolute value is needed. If slopes change about 5 percent through a time period, new readings should be obtained to reach an average cost as before.

4. The tractor operator's efficiency. An operator's efficiency must be judged by comparing his output with that of other operators. Logging contractors have been found to be good judges of the capabilities of their workers. If a man is new on the job and inexperienced, he usually rates in the lower half of a "below average" wedge (see the second or operator efficiency graph on any chart). Notice that the operator efficiency graph allows for the possibility that an operator might be twice as good or twice as bad as another.

A typical path for entering the charts is traced on figure 1 (see superimposed bold dots) as an example. Here the tractor size is small--between 25 and 40 DBHP--and the operator sets his own chokers. In this example, the contractor estimates the distance from deck-to-log area to be 580 feet, terrain conditions best fit class 3, a clinometer shows the slope to average about 28 percent, and the operator is believed to be average based on his production.

Begin at the top graph and follow the dotted path. Run horizontally across from 580 feet using the grid lines as guides and enter terrain class 3. The slope key shows that the right half of a class contains slopes from 22 to 30 percent; hence, interpolate 28 percent just short of the 30 percent bold line on the right border of the terrain class 3 wedge. Drop straight down parallel with grid guide lines into the graph directly below and stop in the middle of the "average" wedge. At this stage, the four estimated factors have been accounted for. Now cross over to the adjoining graph and stop at a point corresponding to that point in the previous graph: from the center, in this example, of the white wedge in the second graph to the center of the white wedge in the third graph. From this point follow the grid lines down into the bottom graph, stopping at the "average" line for hourly owning and operating costs. If records are kept of owning and operating costs, choose a point closest to your figure--interpolate if necessary--instead of using the "average" cost line. Now, go horizontally across to the right axis and pick off the skidding cost estimate. In this example, this estimate approximates $7.50/MBF.

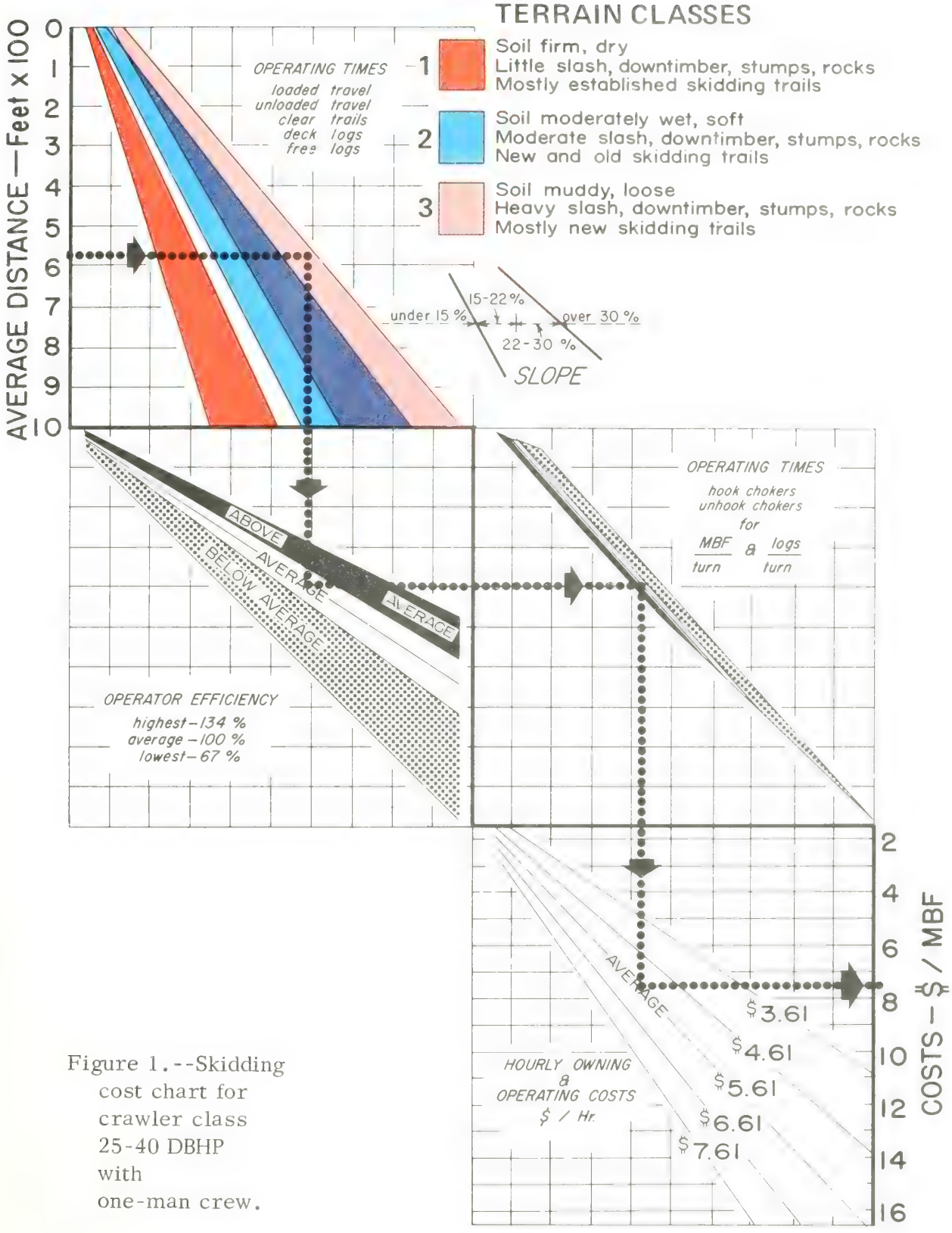

Figure 1.--Skidding cost chart for crawler class 25-40 DBHP with one-man crew.

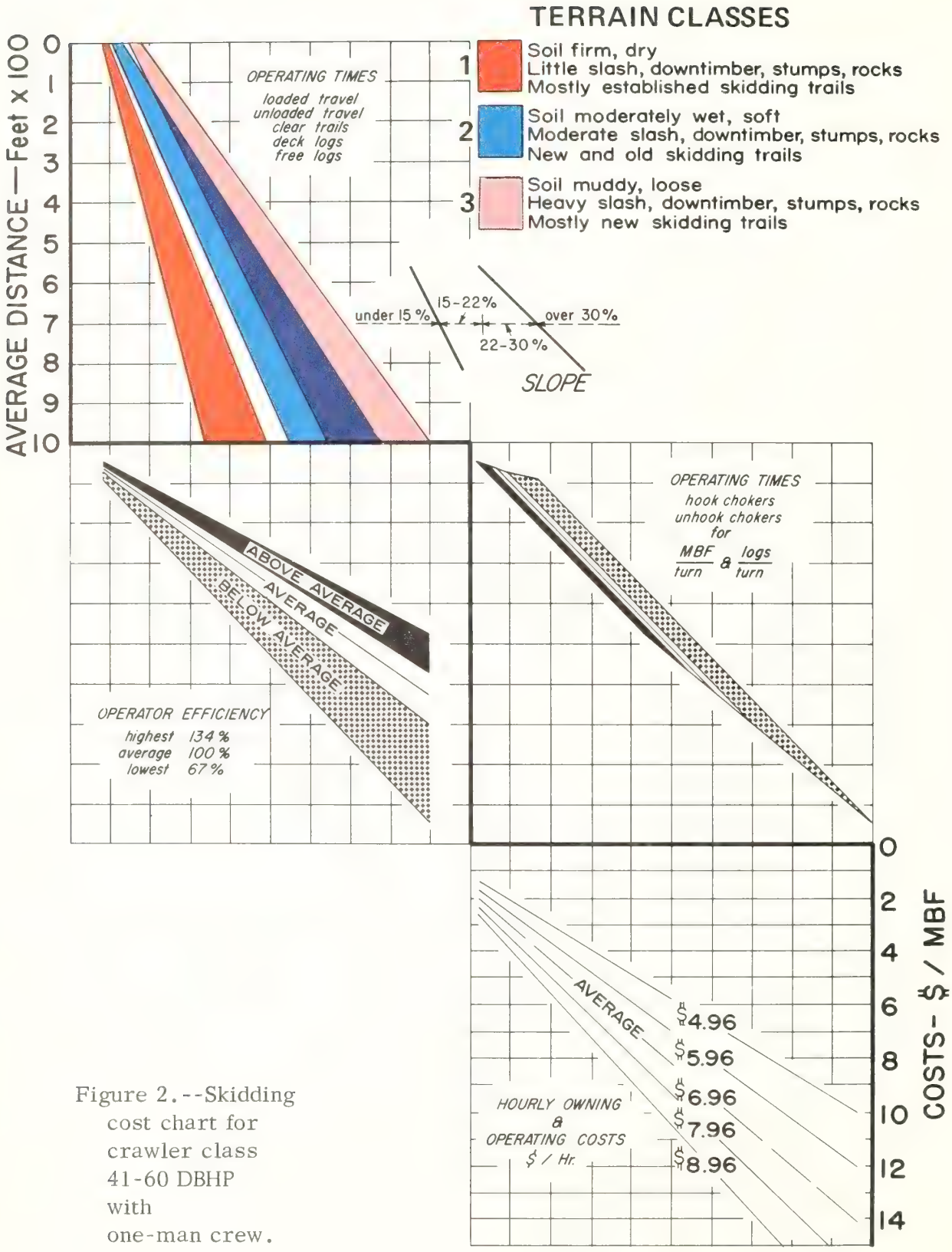

Figure 2.--Skidding cost chart for crawler class 41-60 DBHP with one-man crew.

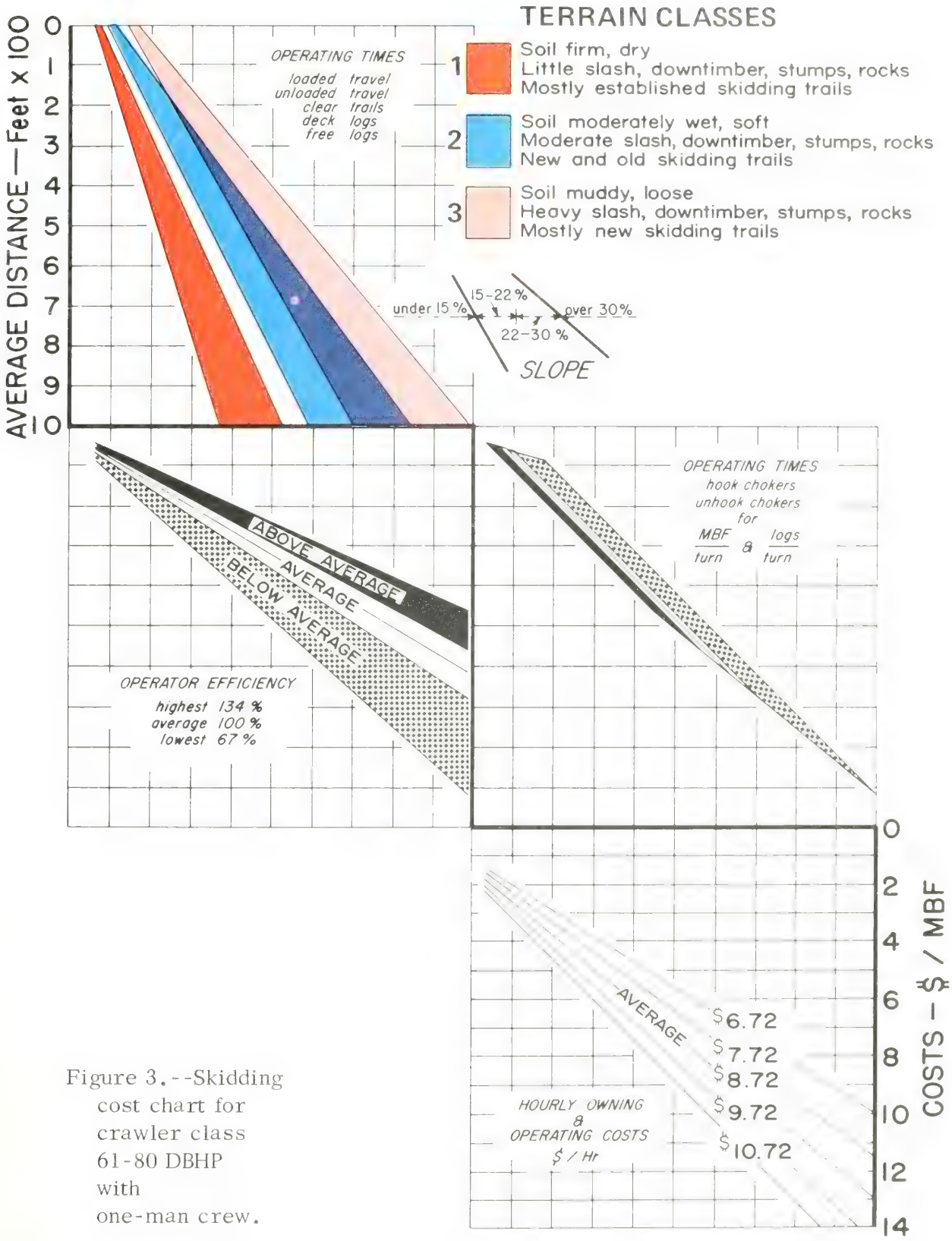

Figure 3.--Skidding cost chart for crawler class 61-80 DBHP with one-man crew.

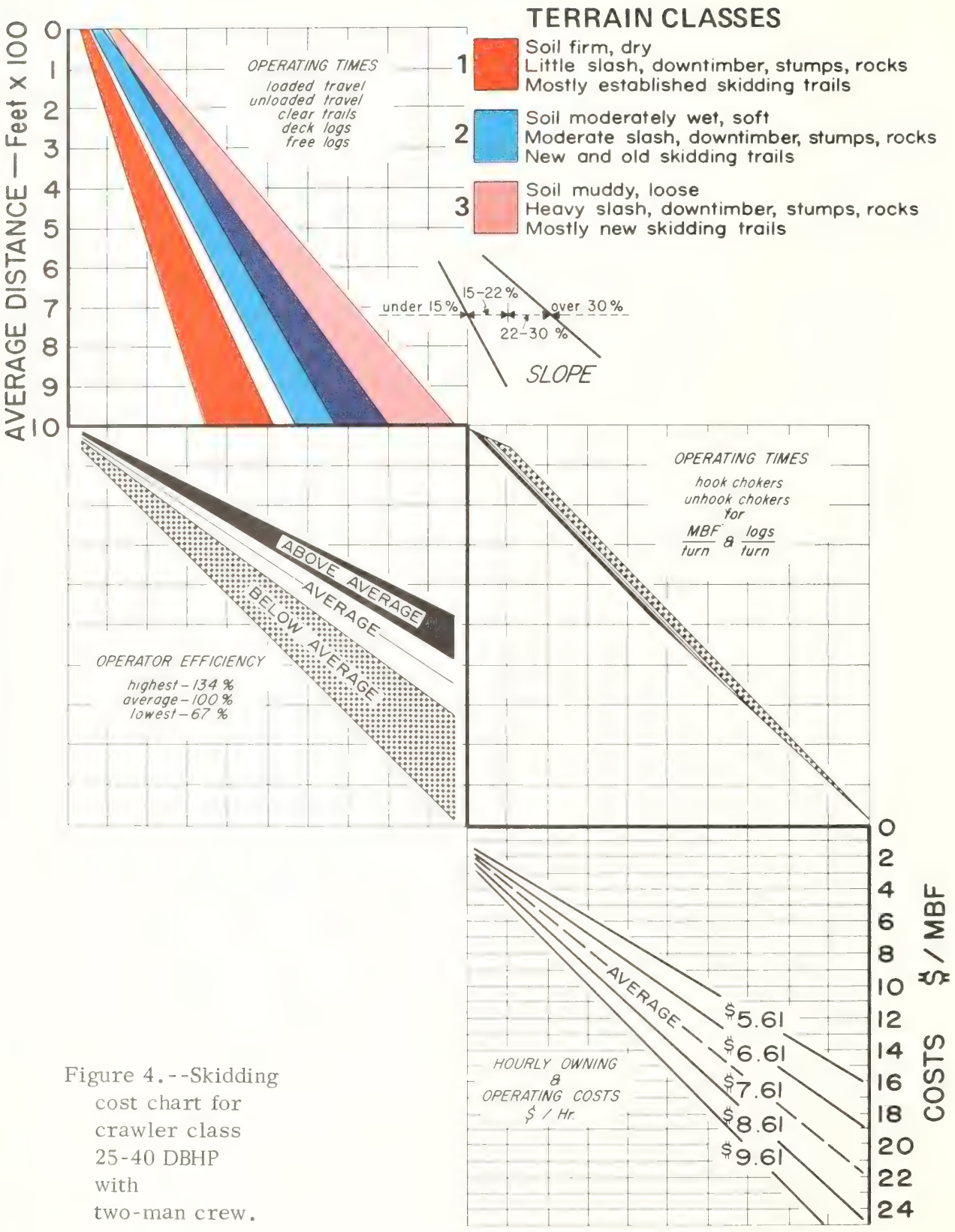

Figure 4.--Skidding cost chart for crawler class 25-40 DBHP with two-man crew.

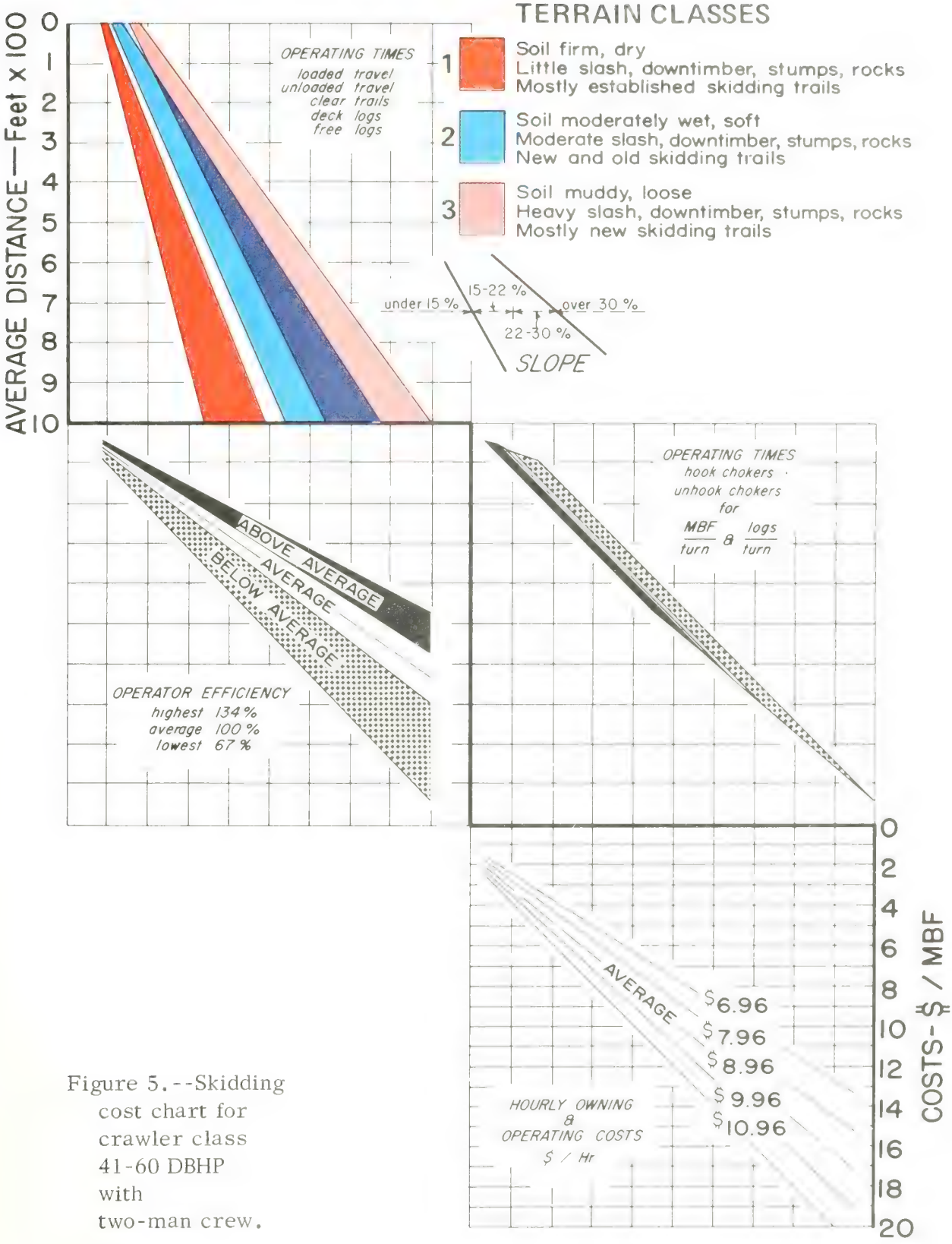

Figure 5.--Skidding cost chart for crawler class 41-60 DBHP with two-man crew.

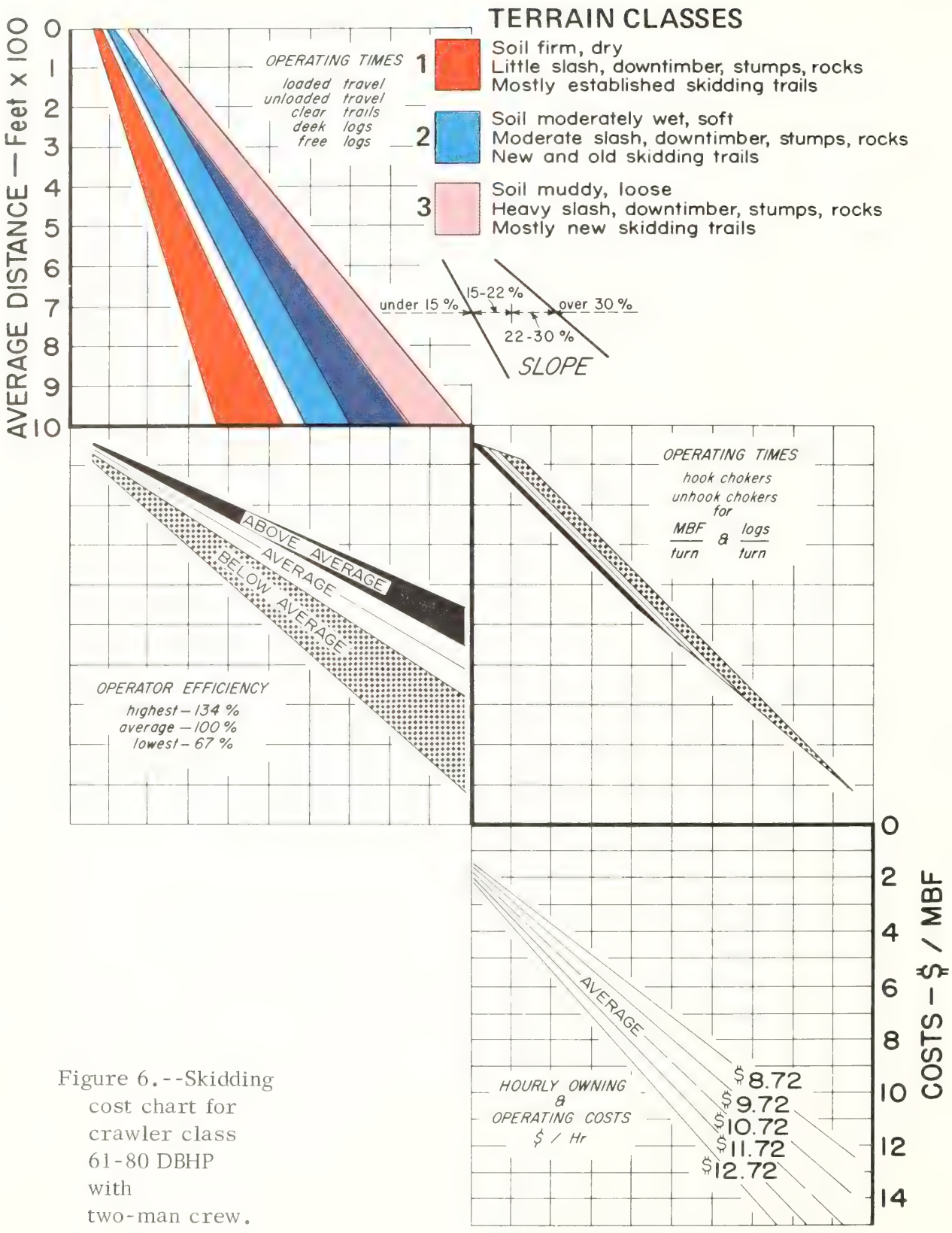

Figure 6.--Skidding cost chart for crawler class 61-80 DBHP with two-man crew.

OPERATING ALTERNATIVES

Figures 7 through 10 permit the contractor to rapidly determine the most economical combination of crawler and crew size for operating under ideal, average, and severe operating conditions for distances up to a thousand feet. These three operating conditions were defined as follows:

	Ideal	Average	Severe
Terrain class (as defined in figs. 1-6)	1	2	3
Slope	<15%	15-22%	>30%
Operator efficiency	110%	100%	90%
Hourly owning and operating costs:			
25-40 DBHP:			
One man	$4.61	$ 5.61	$ 6.61
Two men	6.61	7.61	8.61
41-60 DBHP:			
One man	5.96	6.96	7.96
Two men	7.96	8.96	9.96
61-80 DBHP:			
One man	7.72	8.72	9.72
Two men	9.72	10.72	11.72
Logs/turn:			
25-40 DBHP	4.044	4.044	4.044
41-60 DBHP	5.282	5.282	5.282
61-80 DBHP	6.711	6.711	6.711
BF/turn:			
25-40 DBHP	397	397	397
41-60 DBHP	487	487	487
61-80 DBHP	635	635	635
Log lengths	16-35 ft.	16-35 ft.	16-35 ft.
Log volumes	60-140 BF	60-140 BF	60-140 BF

Figure 7 shows that as operating conditions become worse for a one-man crew (no choker setter), the largest crawler class becomes and remains the most economical choice. Only under ideal conditions and for operations within 200 feet of the deck does the smallest crawler class appear slightly better than the largest. In figure 8 the largest crawler class is the best choice for a two-man crew (operator has a choker setter) without exception. Figure 9 shows that it is more economical to operate with

a one-man crew than with a two-man crew under average conditions; in short, a choker setter does not pay his own way under such conditions. Figure 10 shows where certain two-man crew operations are more economical than one-man crew operations. Specifically, a two-man crew using a crawler of the largest class costs less than a one-man crew using a crawler from either remaining class under average conditions for distances up to 350 feet. Also a two-man crew using the crawler of the largest class is better than a one-man crew using a crawler of the smallest class under severe conditions. Other trade-off comparisons may be seen by the user.

Those interested in applying results from this section are reminded that the trade-off areas are derived strictly from averages gained over a period of data gathering in the Forests mentioned earlier. This means that an experiment was not designed to give confidence limits on the results shown. Hence, trade-offs in figures 7-10 will no doubt deviate to some extent and should be used with caution.

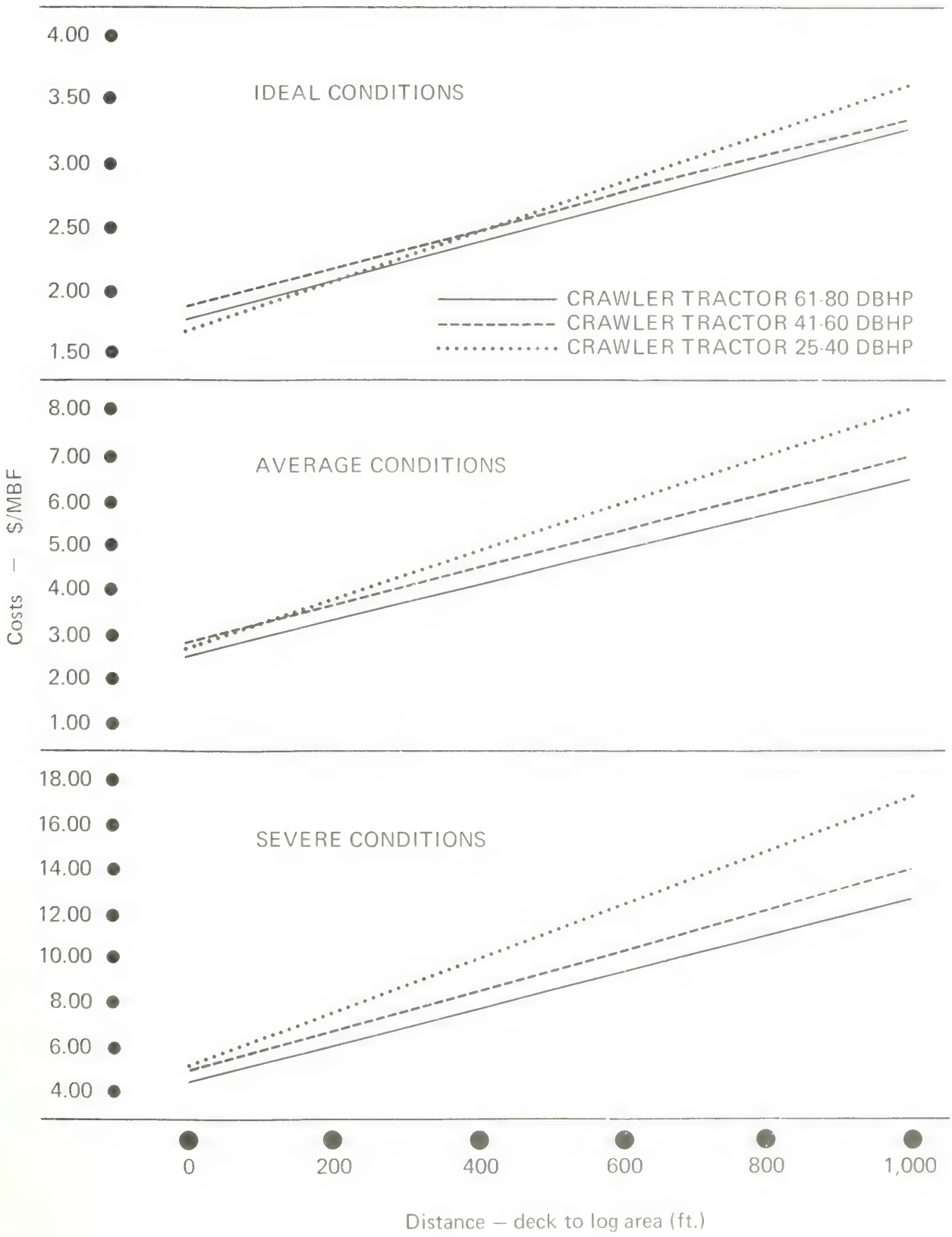

Figure 7.--Skidding costs under three defined operating conditions with one-man crew.

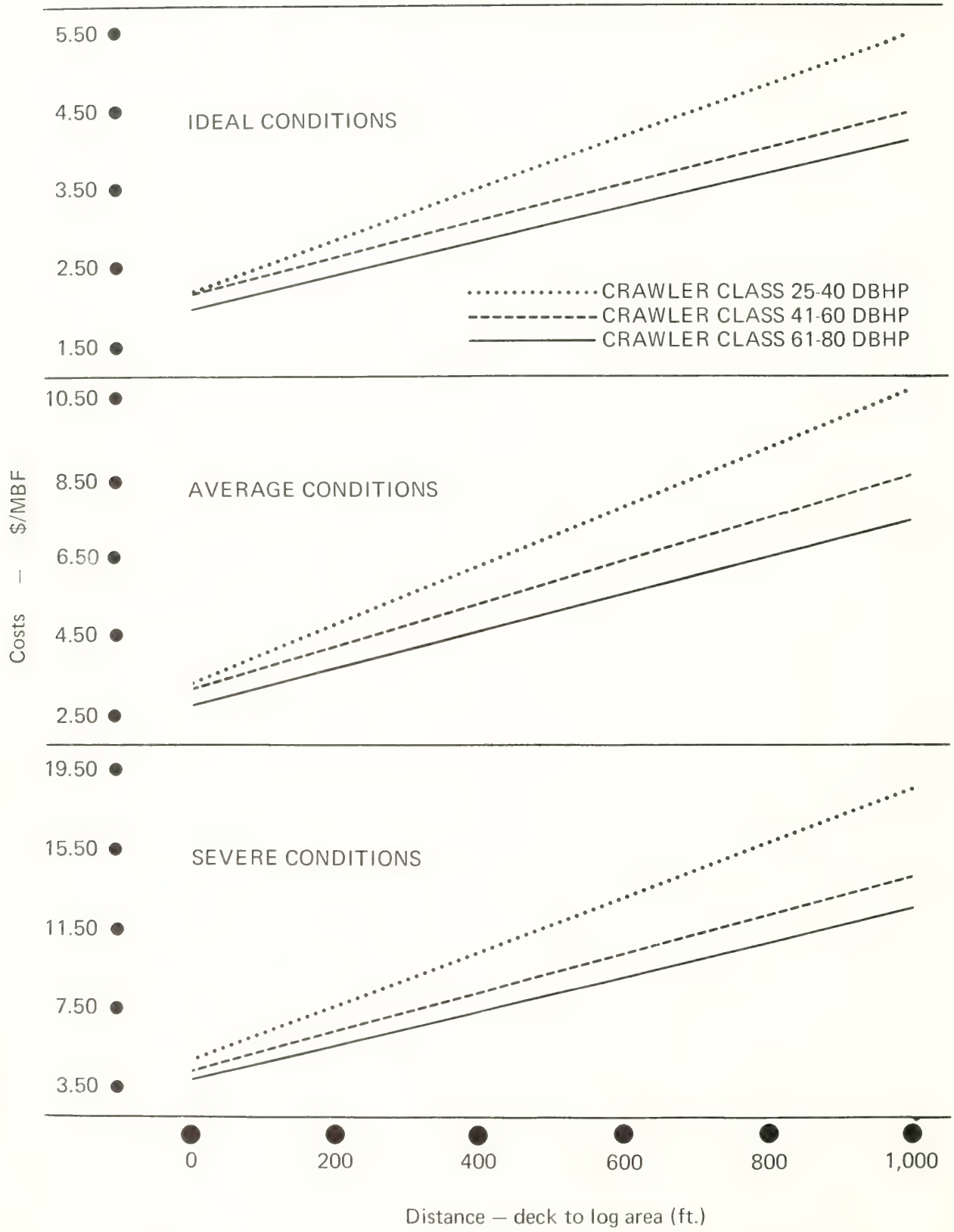

Figure 8.--Skidding costs under three defined operating conditions with two-man crew.

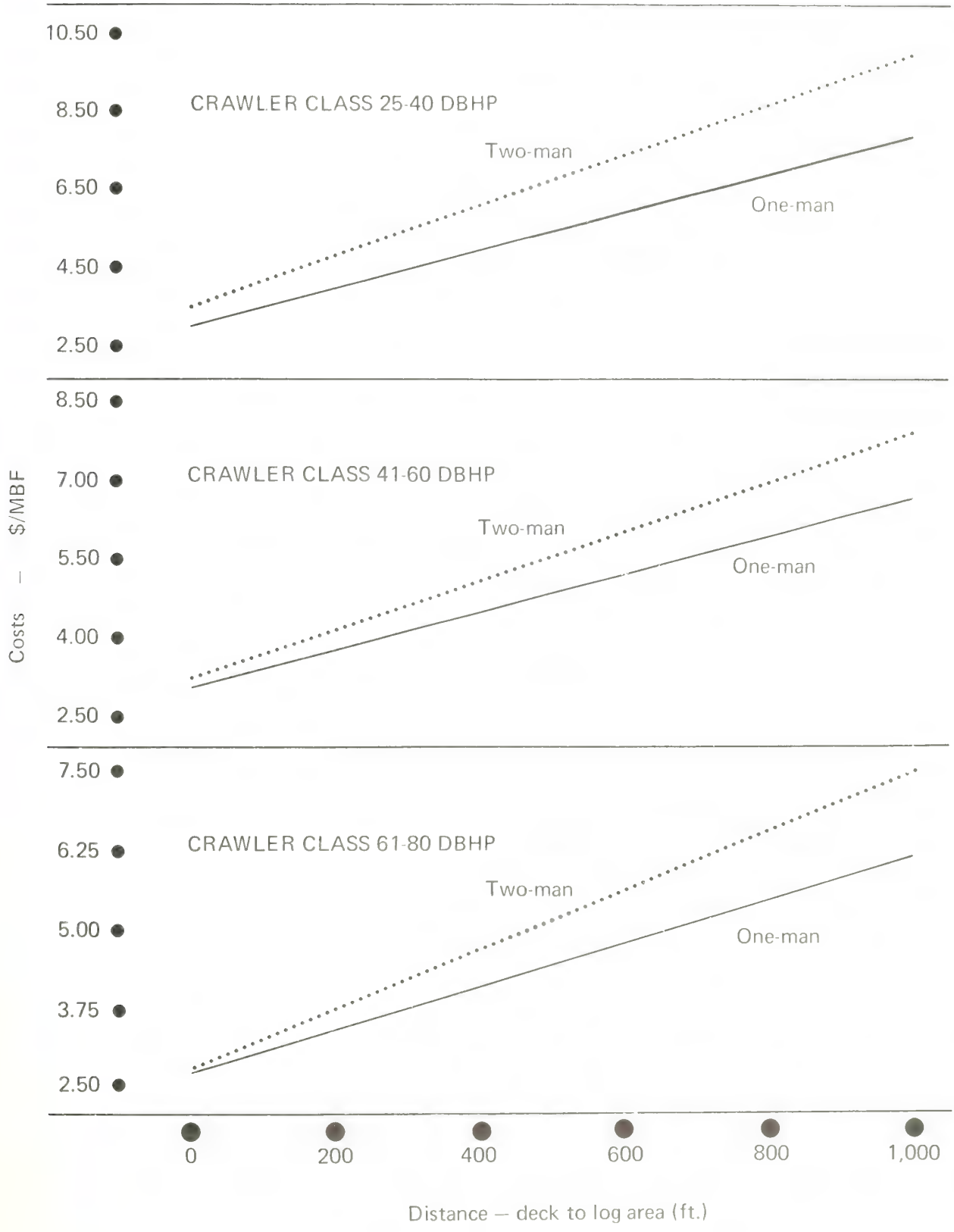

Figure 9.--Skidding costs under average operating conditions with both one-man and two-man crews.

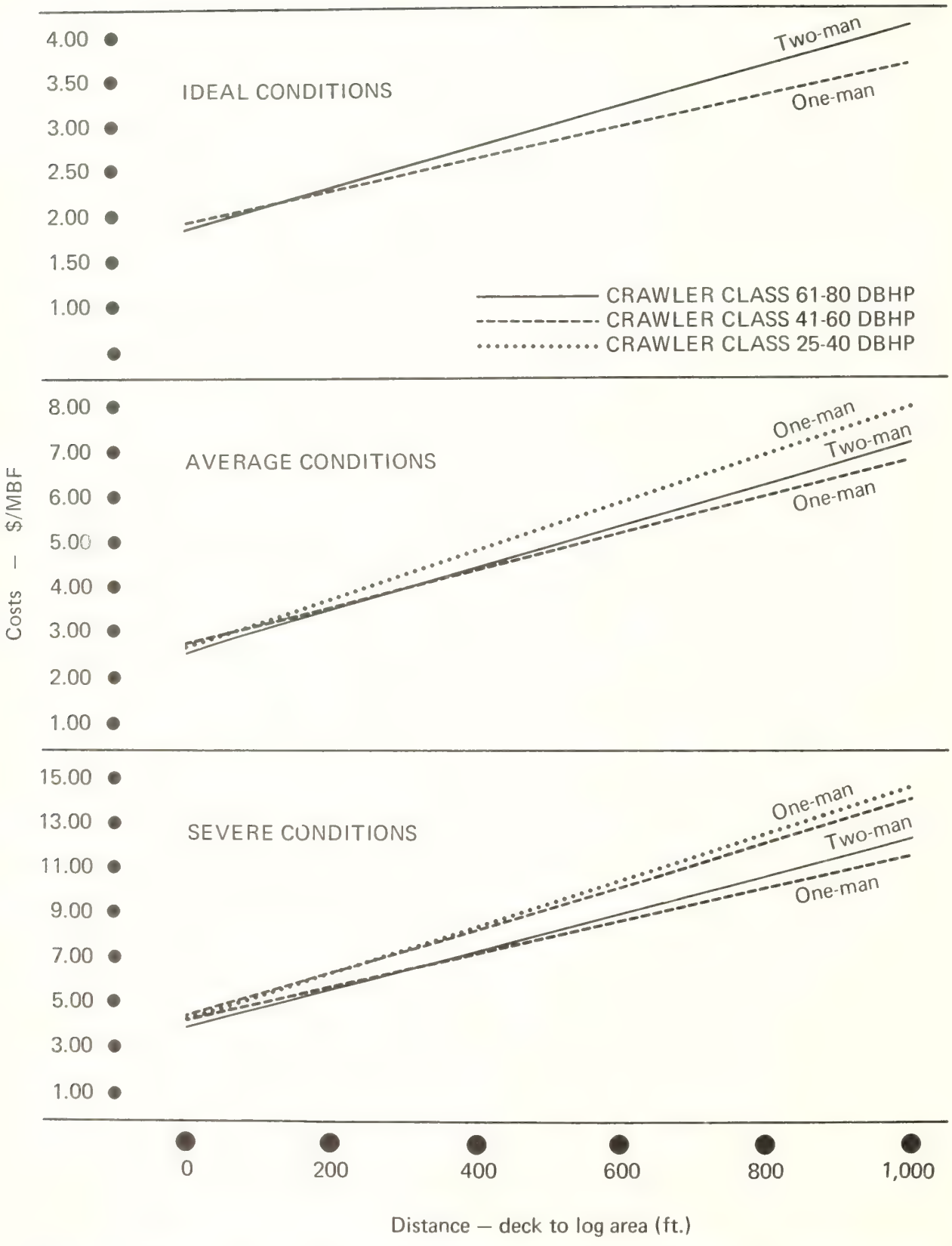

Figure 10.--Skidding costs under three defined operating conditions with both one-man and two-man crews.

APPENDIX

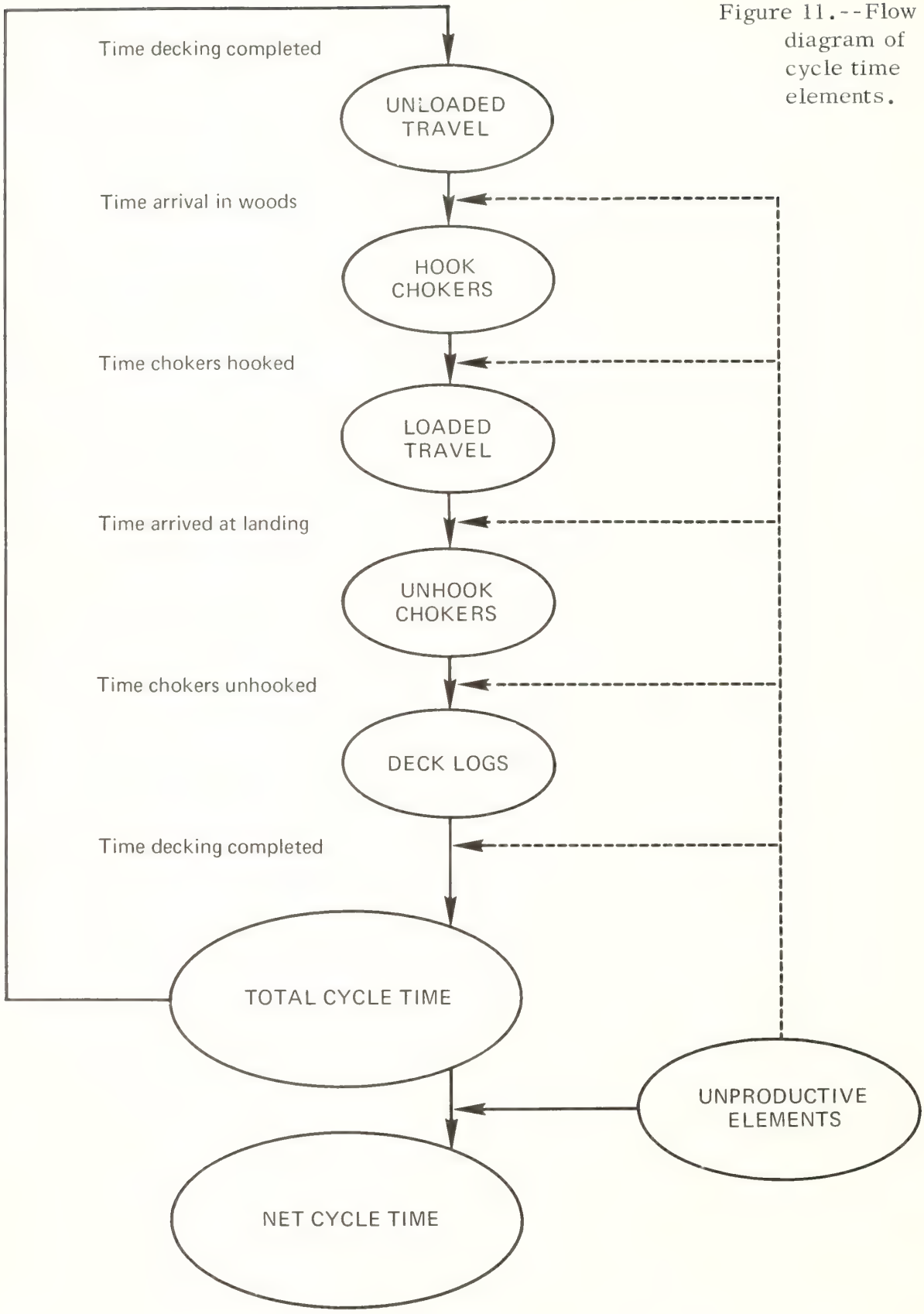

Figure 11.--Flow diagram of cycle time elements.

Cycle Time

The cycle time for crawler tractor skidding is illustrated by the flow diagram on facing page (fig. 11). Total cycle time consists of the accumulation of the five elapsed time intervals for the productive time elements shown in the smaller enclosures and the elapsed time intervals of unproductive time elements (includes delays resulting from equipment breakdown, personnel "breaks," adverse weather, etc.). The dotted lines are intended to indicate that such unproductive time elements might occur at any time during the cycle. Unproductive time elements must be subtracted from the total cycle time to get a net cycle time--the time considered for production rates. To the left of and straddling the five production elements are data commands. The elapsed time between two consecutive commands determines a time interval, providing the effect of unproductive elements is considered. A continuous decimal hour time study was used. For example,

Data command	Decimal hour
Time arrival in woods	0.0560
Time operator begins rest period	.0640
Time operator ends rest period	.0930
Time chokers hooked	.1170

Thus "HOOK CHOKERS" took 0.0610 hour total. Subtracting the unproductive time element "REST," which took 0.0290 hour, get 0.0320 hour net. Unproductive time element interruptions were defined as they occurred, recorded in the margins, and subtracted at the end of each day.

The following definitions assured standardization among data gathered by different people:

Data command	Definition
Time arrival in woods:	
One man	Operator dismounts crawler
Two men	Choker setter grasps winch or choker line
Time chokers hooked:	
One man	Operator mounts crawler
Two men	Last choker is hooked
Time arrived at landing	Operator dismounts crawler
Time chokers unhooked	Operator mounts crawler
Time decking completed	Crawler begins forward motion
Unproductive time elements	As observed, recorded separately

Under "OPERATING TIMES" in graphs 1 and 3 of the six charts, seven time elements are shown, five of which are the productive time elements shown in figure 11. The two remaining elements, shown in graph 1 of the charts, are "clear trails" and "free logs." Both began as unproductive time elements but eventually were considered productive and essential to the skidding operation; hence, they were added to cycle time. "Clear trails" is the time required to clear debris from skidding trails during each cycle. "Free logs" is the time necessary to winch logs clear of restraints.

Table 1.--Basic travel times per 50 feet increments[1]

Terrain class	Slope	Crawler class 25-40 DBHP		Crawler class 41-60 DBHP		Crawler class 61-80 DBHP	
		Unloaded	Loaded	Unloaded	Loaded	Unloaded	Loaded
	Percent	Hour					
Class 1							
	0-15	0.0045	0.0060	0.0042	0.0037	0.0041	0.0036
As defined in	15-22	.0053	.0071	.0050	.0044	.0049	.0044
figures	22-30	.0057	.0076	.0053	.0047	.0052	.0048
1-6	over 30	.0066	.0088	.0062	.0054	.0060	.0053
Class 2							
	0-15	.0073	.0097	.0068	.0060	.0066	.0058
As defined in	15-22	.0086	.0115	.0080	.0072	.0079	.0070
figures	22-30	.0092	.0122	.0086	.0077	.0084	.0076
1-6	over 30	.0110	.0142	.0100	.0088	.0097	.0085
Class 3							
	0-15	.0082	.0109	.0076	.0067	.0075	.0065
As defined in	15-22	.0097	.0130	.0091	.0080	.0089	.0078
figures	22-30	.0103	.0138	.0096	.0086	.0094	.0085
1-6	over 30	.0120	.0160	.0112	.0099	.0109	.0096

[1]Average times from 24 to 72 turns most situations. Interpolations made where data incomplete.

Controlling Variables

Cycle time variations respond to eight controlling variables. The variables are met as a user progresses through any of the charts. In graph 1, distance, terrain, and slope affect cycle time. Dropping down into graph 2, the fourth variable met is operator efficiency. In graph 3, MBF/turn (size of logs) and logs/turn (number of logs) tie down the production rate. The right combination of crawler class and crew size variables determine which chart to select.

Hourly Owning and Operating Costs

Hourly owning and operating costs are found in graph 4 on the charts. The costs are introduced in the last graph to translate production rates to production costs. These costs, which are shown on page 9, include total depreciation (initial cost less salvage value), interest, insurance, taxes, fuel, lubricants, repairs, parts, workmen's compensation, and operator's wages.

Constructing the Charts

Graph 1 is assembled from the following:

1. Arbitrary skidding distance scale (1,000 feet chosen for maximum conceivable distance).
2. Travel times under varying conditions of terrain, slope, and crawler size (table 1).
3. Average times to clear trails for three terrain classes defined in figures 1-6: class 1, 0.0057 hour; class 2, 0.0113 hour; and class 3, 0.0330 hour.
4. Average times to deck logs for different class crawlers: 25-40 DBHP, 0.0200 hour; 41-60 DBHP, 0.0166 hour; and 61-80 DBHP, 0.0161 hour.
5. Times to free logs (0.0101 hour per turn average regardless of crawler size).

In the following formula, all times are entered in decimal hours and all distances in feet. Results are in decimal minutes/turn with an allowance for distances spent maneuvering around landings.

[travel unloaded time + travel loaded time] [(1.2 X distance) + 120] +

[clear trail time + deck logs time + free logs time] 60 = minutes/turn.

Using this formula, the wedges shown in the first graph of each chart are set up throughout the range of distances and combinations of operating conditions for terrain and slope. The scale at the bottom of this graph has output values from the formula in minutes/turn. Actual output values from individual graphs are not shown until reaching the final chart output in $/MBF. Notice that choker handling times and log volumes, both of which are needed to complete the production cycle, do not appear in the first graph.

Graph 2 simply increases or decreases the output in minutes/turn from graph 1, according to the efficiency rating of the operator. Hence the output grid, located on the right border, is set up to accommodate the extremes of operator efficiency--from 67 percent under the most severe operating conditions to 134 percent under the most ideal. If an output value from graph 1 is 5 minutes/turn, it is upgraded to 4 minutes/turn when an operator receives a 125-percent efficiency rating; it is downgraded to 6.67 minutes/turn when an operator is about 75-percent efficient.

The formula for graph 2, in which operator efficiency is always entered in decimal form, follows:

[input minutes/turn (from upper grid)]/operator efficiency = output minutes/turn (on right grid).

Graph 3 is assembled from

1. Average MBF/turn depending upon crawler class (tabulation, page 9).

2. Average number of logs/turn depending upon crawler class (tabulation, page 9).

3. Average times/log for handling chokers according to crawler class and crew size (table 2).

Table 2.--Average times per log for handling chokers

Crawler class	Crew size	Choker operation	
		Hooking	Unhooking
		Hour	
25-40 DBHP	One man	0.0216	0.0066
	Two men	.0172	.0044
41-60 DBHP	One man	.0190	.0059
	Two men	.0151	.0038
61-80 DBHP	One man	.0138	.0045
	Two men	.0110	.0030

Total cycle time is found by

$$[\text{logs/turn}][\text{hook chokers time} + \text{unhook chokers time}]\frac{60}{\text{operator efficiency}} + \text{minutes/turn (from left grid)},$$

where choker handling times are entered as decimal hours. The bottom grid must have a production rate output in minutes/MBF; thus divide the total cycle time by turn volume to complete graph 3, or

1,000[total cycle time (from above)]/BF/turn = minutes/MBF.

Graph 4 takes the outputs from graph 3 on the upper grid, combines them with the costs corresponding to the proper crawler sizes (tabulation, page 9), and converts production rates to a measure of effectiveness in $/MBF, or

[minutes/MBF(output from graph 3)][hourly owning and operating costs]/60 = $/MBF (chart output).

Of course, averages in any of the four graphs on each chart may be changed to suit user modifications. Beginning at the point of modification, output grids must be revised until a new output grid for each chart in $/MBF is attained.

Schillings, Paul L.

1969. Selecting crawler skidders by comparing relative operating costs. U.S. Dep. Agr., Forest Serv., Intermountain Forest and Range Exp. Sta., Ogden, Utah 84401. 20 pp., illus. (USDA Forest Serv. Res. Pap. INT-59)

Costs of skidding with 25- to 80-drawbar hp. crawler tractors in southwestern Montana are analyzed and compared. Data include operating times, terrain classes, steepness of slopes, efficiency of operators, costs of owning and operating, and log production. Charts enable a user to quickly estimate skidding cost per MBF considering distance from log deck to log-making area, type of terrain, average slope, and efficiency of operator.

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Brigham Young University)

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A TECHNIQUE FOR COMPARING THE COSTS OF SKIDDING METHODS

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UNIVERSITY OF CALIFORNIA

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Research Paper INT-60
1969

A TECHNIQUE FOR COMPARING THE COSTS OF SKIDDING METHODS

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INTRODUCTION

The nine tables presented on pages 15-23 permit a logging operator to compare relative operating costs among five different skidding methods. Tables 1-4 provide data for operations in which crawler tractors ranging from 25 to 130 drawbar horsepower (DBHP) are used; tables 5 and 6 for operations in which rubber-tired vehicles with a 55-80 or 81-117 brake horsepower (BHP) rating are used; table 7 for high-lead operations in which portable towers are used; table 8 for Idaho jammer operations, which consisted of a portable boom with a continuous haul-back line and chokers in every operation observed; and table 9 for what are called "shovel logging" operations.

The costs in these tables represent estimates based upon observations made at one shovel logging operation, eight portable tower operations, and from 10 to 20 different operations employing each of the three remaining skidding methods.

The shovel logging operation was found on the Gallatin National Forest, which is located in the vicinity of Bozeman, Montana. The rig consisted of a portable boom in which the A-frame is either of logs or fabricated steel and single drum pulley with a half-inch line and tongs. An operator worked along a skidding road or trail, casting the tongs either downhill 125 feet or uphill as far as 50 feet. Some tong setters carried tongs beyond the downhill cast another 25 feet, which allowed a maximum skidding distance of 150 feet. A good operator was capable of releasing the tongs from a log without leaving the cab. One log was handled at a time. We found that this method was uneconomical when skidding distances were beyond 150 feet.

Among the high-lead operations studied, towers ranged from 40 to 70 feet high and power plants ranged from 165 to 225 BHP. Remote-controlled carriage units were not used in any of these operations. High-lead operations were found to be the most economical in situations where skidding distances were over 500 feet and where there were steep slopes, large trees, and high acre densities.

For most operations observed, rubber-tired vehicles were found to be the most economical, assuming equal operator efficiencies. This is reflected by the increasing use of these vehicles throughout the country. In our contacts, however, we found some contractors who felt that downtime and operator unfamiliarity with rubber-tired vehicles do not permit them to realize maximum potential efficiency from such skidders. Furthermore, they preferred crawler tractors because they are needed in other phases of logging operations.

Not all of the operations studied were cutting logs large enough to fall within the 4, 6, or 8 logs/MBF categories. Therefore, costs had to be extrapolated using the mathematical model described in the Appendix. For example, in tables 1, 5, and 9, extrapolated values are used for all three of these categories; in tables 2 and 6, for only the 4 and 6 logs/MBF categories; and in table 3, for only the 4 logs/MBF category. Extrapolated costs are so indicated by being enclosed in rectangles on these tables.

Extrapolated costs can be compared directly with other extrapolated costs. However, when estimated costs are used, the lowest estimated cost is considered more economical than the lowest extrapolated cost unless the latter shows a cost savings of at least 20 percent. Those operators who have had experience using the skidding methods for which extrapolated costs are presented may wish to shave this percentage to 15 percent or less. Example 2 on page 3 deals with a situation involving both extrapolated and estimated costs.

HOW TO USE TABLES

Four variables must be known or estimated before entering the cost tables. These are:

1. Area density in MBF/acre, which is presented for a range of from 5 to 15 MBF/acre in steps of five on all of the tables.

2. Skidding distances in feet. In tables 1-7, these are presented in 100-foot steps ranging from 200 to 600 feet. In table 8, the distances range from 100 to 400 feet in 100-foot steps, while in table 9 they range from 25 to 125, in 25-foot steps.

3. Slope in percent, which ranges from 5 to 40 percent in steps of 5 percent on all tables.

4. Number of logs/MBF, or tree size, which ranges from 4 to 16 logs/MBF in steps of two logs on all tables.

Example 1.

Suppose the stand density in an operating area is about 10 MBF/acre, the average skidding distance is 400 feet, the average slope is around 30 percent, and the number of logs/MBF corresponding to the stand density is 14.

Enter table 1. The data under 10 MBF/acre would provide the desired values for the operating conditions given. Look to the left column under "DISTANCE" and stop at the 400 group in the middle of the sheet, then choose the 30-percent slope to the right of the 400 group. You are now on the correct row. Move across the row to the right and stop in the column labeled 14 logs/MBF. The cost estimate is $7.65/MBF.

Next turn to table 2. Proceed as you did in table 1 and you'll get $6.72/MBF. Continuing in this manner using the remaining seven tables, you would derive the following:

	Cost ($/MBF)
Crawler tractor, 25-40 DBHP	7.65
Crawler tractor, 41-60 DBHP	6.72
Crawler tractor, 61-80 DBHP	4.32
Crawler tractor, 110-130 DBHP	7.87
Rubber-tired vehicle, 55-80 BHP	4.04
Rubber-tired vehicle, 81-117 BHP	5.63
High-lead, portable tower	9.02
Idaho jammer	8.71
Shovel (w/tongs)	Not practical

In this example, no extrapolated values were taken; hence, eight of the values may be compared directly. Shovel skidding was not considered because 400 feet is outside its skidding range. We immediately see that the smaller rubber-tired skidder is the most economical, as could be expected because of the low stand density and small logs involved.

PREFACE

During the summer of 1967, David B. Brown and Michael R. Carter, both graduate students in industrial engineering at Montana State University, were temporarily employed by the Station to investigate the economics of skidding systems commonly used in western Montana, Idaho, and northwestern Wyoming.

Brown had completed a thesis entitled "An economic comparison of skidding methods employed in the Northern Rocky Mountain area" in partial fulfillment of the requirements for a master's degree from the University. In it, he compared relative profits of four types of skidding methods--crawlers, wheeled vehicles, cranes, and high-lead towers. During their summer assignment, he and Carter gathered data on a fifth type, coordinated these data with those used in Brown's thesis, and constructed a mathematical model to provide comparative cost information on these five types of skidding methods. They chose to substitute "costs" for "profits" as the measure of comparison to avoid confounding their task because (1) some company policies preclude general dissemination of profit and loss information, and (2) fluctuating market conditions affect profits.

Lack of time cut short the data collection necessary to fully satisfy the objectives of the study. Most of the values in the tables are based on information obtained within a 75-mile radius of Bozeman, Montana. The values presented in the cost tables should be viewed as tentative--as estimates based only on information that was available at the time of the study. Furthermore, the author recognizes that these estimates can be upgraded in terms of accuracy when additional data are gathered in future studies. However, the tables are presented at this time purely for their possible interest to contractors, who shouldn't assume the values will accurately apply to their particular operations.

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Example 2.

Assume a thin stand has large timber on moderately steep slopes where average skidding distances run up to 600 feet. Assume further that high-lead equipment is not available. The variables for this situation: area density, 5 MBF/acre; skidding distance, 600 feet; slope, 40 percent; and tree size, 4 logs/MBF. Using the same procedure as you did in Example 1, you would derive the following:

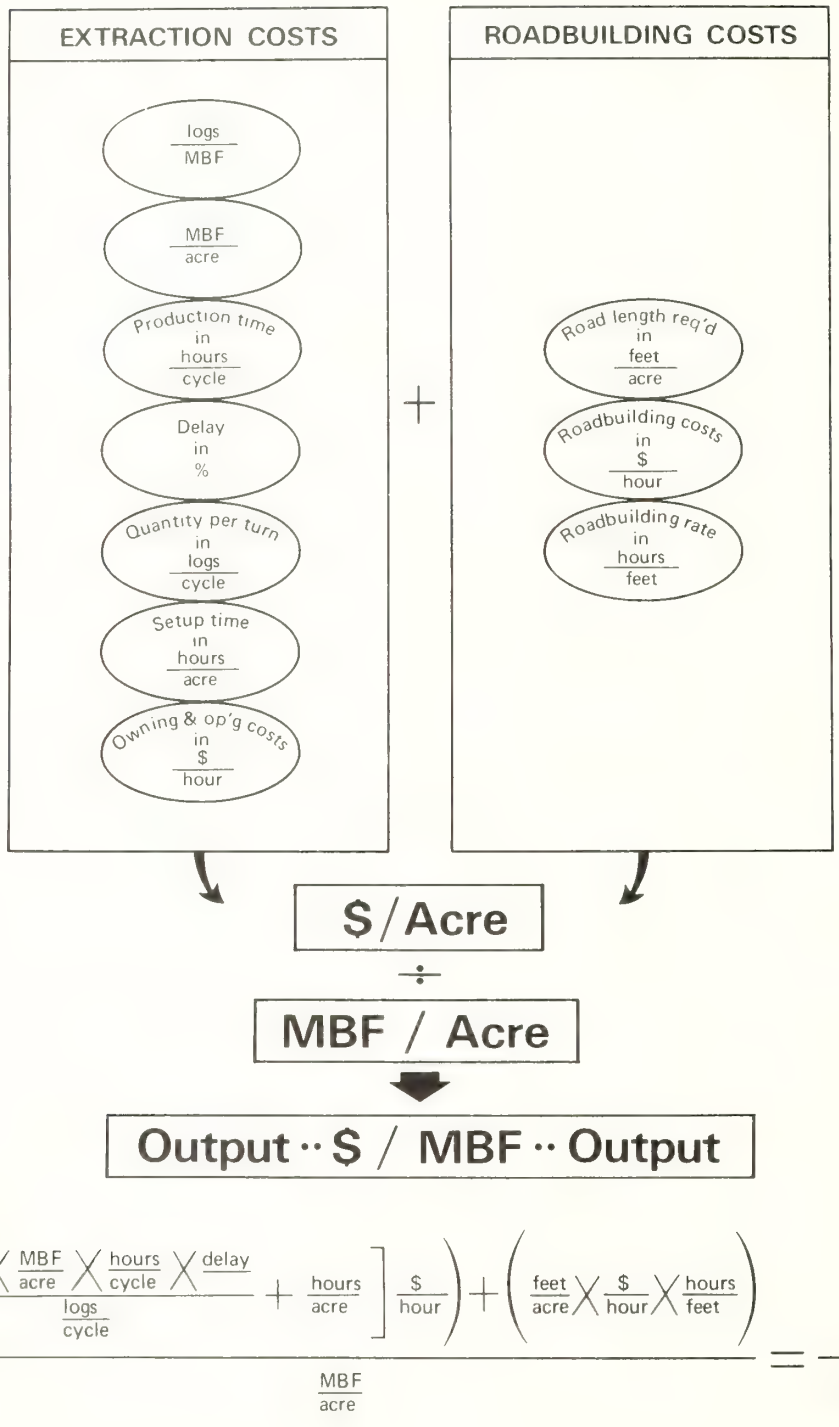
Skidding type	Cost ($/MBF)
Crawler tractor, 25-40 DBHP	5.89*
Crawler tractor, 41-60 DBHP	4.49*
Crawler tractor, 61-80 DBHP	2.90*
Crawler tractor, 110-130 DBHP	3.68
Rubber-tired vehicle, 55-80 BHP	2.88*
Rubber-tired vehicle, 81-117 BHP	4.09*
High-lead, portable tower	Not available
Idaho jammer	Not applicable
Shovel (w/tongs)	Not applicable

*Extrapolated values

As noted earlier, shovel logging is limited to a maximum skidding distance of 150 feet and couldn't be used in this situation. Furthermore, we didn't view the use of the Idaho jammer method as being applicable because among the operations studied none were for skidding distances of over 400 feet. This is not to say that the Idaho jammer can't be used for skidding longer distances.

Although the skidding cost for the 55-80 BHP rubber-tired vehicle is an extrapolation, it does represent a savings of at least 20 percent over the lowest estimated cost ($3.68 for the 110-130 DBHP crawler tractor). The cost for the 61-80 DBHP crawler tractor also represents savings of at least 20 percent; thus, for all practical purposes it would be as economical to use the crawler tractor as it would be to use the smaller rubber-tired skidder. Your choice would rank as follows: (1) rubber-tired vehicle, 55-80 BHP, (2) crawler tractor, 61-80 DBHP, (3) crawler tractor, 110-130 DBHP, (4) rubber-tired vehicle, 81-117 BHP, etc. The level of 20 percent is set arbitrarily as a guide and may be changed at the discretion of the operator.

APPENDIX


EXTRACTION COSTS
logs / MBF
MBF / acre
Production time in hours / cycle
Delay in %
Quantity per turn in logs / cycle
Setup time in hours / acre
Owning & op'g costs in $ / hour
+
ROADBUILDING COSTS
Road length req'd in feet / acre
Roadbuilding costs in $ / hour
Roadbuilding rate in hours / feet
$/Acre
÷
MBF / Acre
Output ·· $ / MBF ·· Output

$$\frac{\left(\left[\frac{\text{logs}}{\text{MBF}} \times \frac{\text{MBF}}{\text{acre}} \times \frac{\text{hours}}{\text{cycle}} \times \frac{\text{delay}}{\frac{\text{logs}}{\text{cycle}}} + \frac{\text{hours}}{\text{acre}}\right] \frac{\$}{\text{hour}}\right) + \left(\frac{\text{feet}}{\text{acre}} \times \frac{\$}{\text{hour}} \times \frac{\text{hours}}{\text{feet}}\right)}{\frac{\text{MBF}}{\text{acre}}} = \frac{\$}{\text{MBF}}$$

Figure 1.--Flow diagram of the mathematical model is shown above; the dimensional equation for this model is shown below.

INPUT DESCRIPTIONS

EXTRACTION COSTS

Extraction costs are made up of the seven inputs shown in figure 1.

MBF/acre is a situation variable called density, which may be determined from a timber cruise or from contractors' records. It is designated either "XBFPA" or "MBFPA" in the computer program (see p. 14). Defect averaged 10 percent.

Logs/MBF also is a situation variable and is readily judged by experienced contractors. Its program designation is "XGPMBF" or "LGPMBF." Log lengths ranged from 16 to 40 feet.

Hours/cycle denotes production time and is generated by the following multiple-regression equation:

$$y = a_0 + a_1x_1 + a_2x_2 + a_3x_3,$$

where

y = cycle (turn) time in hours
x_1 = skidding distance
x_2 = slope
x_3 = number of logs per cycle

Briefly, the equation gives cycle time in hours based on the three most significant variables we found--skidding distance, slope, and number of logs skidded during each cycle. The constants for this equation are as follows:

Skidding type	Regression (a_0)	Distance (a_1)	Slope (a_2)	Logs (a_3)
Crawler tractor, 25-40 DBHP	0.04293	0.0018800	0.0020339	0.02415
Crawler tractor, 41-60 DBHP	.08071	.0000953	.0020964	.02218
Crawler tractor, 61-80 DBHP	.10518	.0002705	− .0020109	.01257
Crawler tractor, 110-130 DBHP	.10736	.0004778	.0013270	.01502
Rubber-tired vehicle, 55-80 BHP	.01222	.0002291	− .0007572	.01912
Rubber-tired vehicle, 81-117 BHP	.08941	.0007040	.0012269	.01182
High-lead, portable tower	.04297	.0000024	.0009517	.00807
Idaho jammer	.00535	.0000475	.0001651	.00000
Shovel (w/tongs)	.01760	.0002081	− .0005169	.00000

The multiple-regression equation is shown in program statement 35, beginning with "RC" (regression constant) and ending with "XLGPC" (number of logs per cycle).

Delays are caused from equipment breakdowns, personnel "breaks," weather conditions, etc. These vary among individual skidding operations. Delay averages as percents of available operating times were established for the various skidding methods as follows: high-lead, portable tower, 20 percent; Idaho jammer, 15 percent; shovel (w/tongs), 20 percent; all

others, 25 percent. These were used in the mathematical model to ensure that the various methods were compared on an equal basis. Delay values are called "DELAY" in the program and entered as decimals.

Logs/cycle was derived by averaging the number of logs observed for each operating cycle. Values averaged from data gathered closely approached the even increment separations as shown below for each of the logs/MBF categories:

	4	6	8	10	12	14	16
Crawler tractor, 25-40 DBHP	1.2	1.8	2.4	3.0	3.6	4.2	4.8
Crawler tractor, 41-60 DBHP	2	3	4	5	6	7	8
Crawler tractor, 61-80 DBHP	3.6	5.4	7.2	9.0	10.8	12.6	14.4
Crawler tractor, 110-130 DBHP	8	12	16	16	16	16	16
Rubber-tired vehicle, 55-80 BHP	1.6	2.4	3.2	4.0	4.8	5.6	6.4
Rubber-tired vehicle, 81-117 BHP	2	3	4	5	6	7	8
High-lead portable tower	4	4	4	4	4	4	4
Idaho jammer	1	1	1	1	1	1	1
Shovel (w/tongs)	1	1	1	1	1	1	1

For example, in the case of the 25-40 DBHP crawler tractor, the separation is exactly 0.6 for each category of log sizes from 4 through 16 logs/MBF. Although it is unlikely that exact separations would be the real case, we assumed linearity because (1) the data closely approximated a straight line, hence it did represent the apparent situation; and (2) the total weight for each turn involving a tracked or wheeled skidder remained essentially the same for each class regardless of the number of logs skidded. Of course, shovels, jammers, and portable towers each skidded the same number of logs/cycle regardless of total weight. Logs/cycle appears in the program as "XXGPC" or "XLGPC."

Hours/acre means setup time for each acre of skidding area covered. It is the elapsed time from the moment a piece of equipment is in its new location until it begins a skidding cycle. This input was not considered applicable to tracklaying and wheeled skidder operations because the equipment is always in movement with its load. Setup times/acre are derived as functions of average skidding distances as follows:

FOR HIGH-LEAD, PORTABLE TOWER OPERATIONS.
(See figure 2 next page for typical area configuration.)

1. Average setup time = 0.84 hour (mean of eight setups, one setup being a single tower positioned with its corresponding tail block locations at A, B, C, D, and E).
2. Area for setup = 250,000 sq. ft. or 5.74 acres.
3. Combining steps 1 and 2 get 0.1463 hour/acre or 0.15.
4. Average skidding distance = 662 feet (distance to centroid of sector assuming uniform density throughout).

5. Multiplying results from 3 and 4 get 97, thus y = 97/x,

where y = setup time/acre
x = average skidding distance
97 = constant written into program as "XETUP" or "SETUP."

At this point, one might question the accuracy of the hyperbolic function which was used to determine setup times for all ranges of skidding distances. It is true that the function was derived without benefit of data to match setup times with various skidding distances. Without this data, we relied upon the most common portable tower configuration as the source for the best values available.

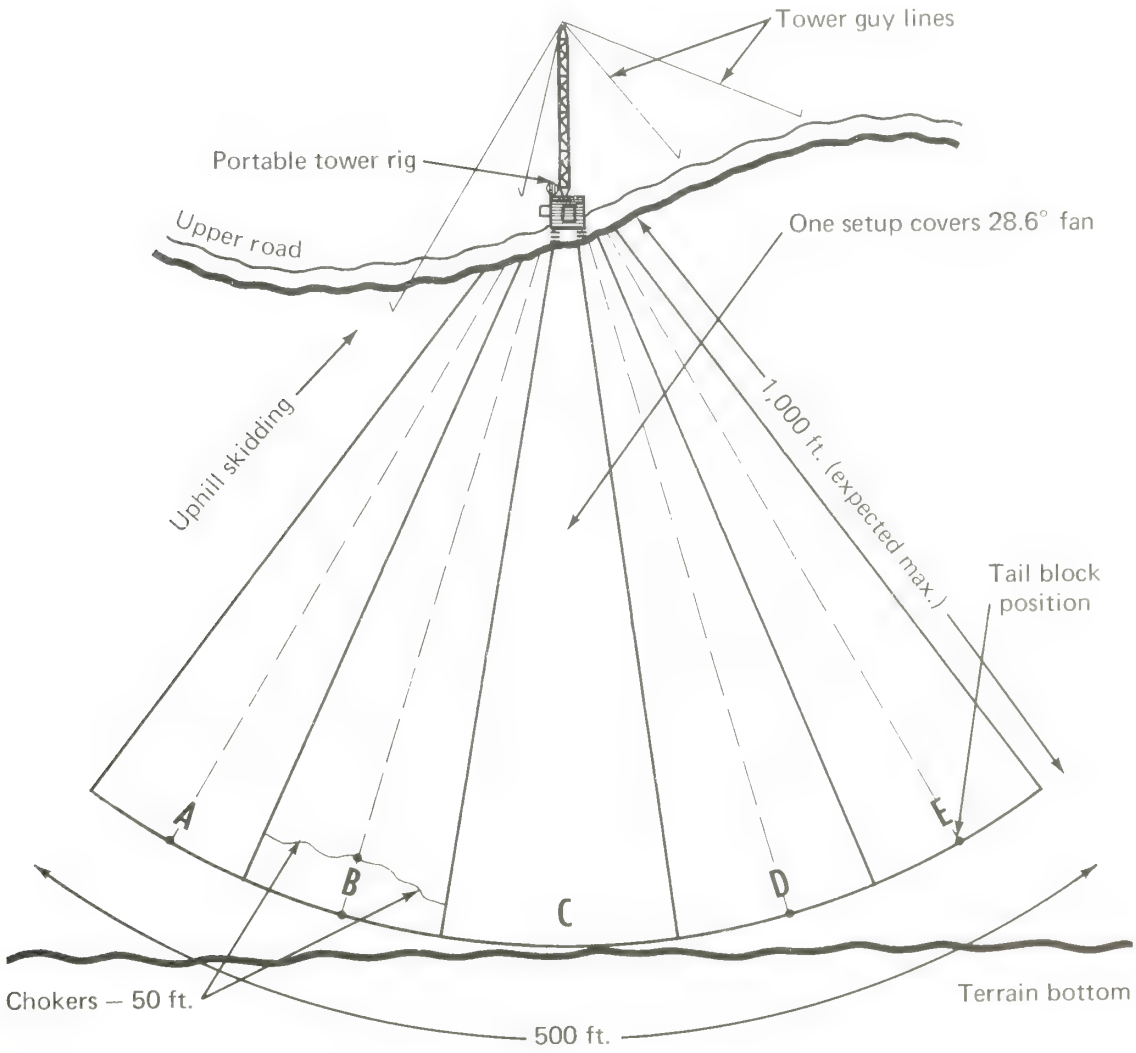


Figure 2.--Typical configuration for a high-lead, portable tower.

FOR IDAHO JAMMER OPERATIONS.
(See figure 3 on facing page for typical area configuration.)

1. Average setup time = 0.416 hour (mean from 12 jammer operations).
2. Area for setup = 40,000 sq.ft. or 0.918 acre.
3. Combining steps 1 and 2 get 0.453 hour/acre.
4. Average skidding distance = 466 feet (slightly beyond center because of diagonal skidding).
5. Multiplying results from 3 and 4 get 211, thus y = 211/x (see explanation in step 5 under "FOR HIGH-LEAD, PORTABLE TOWER OPERATIONS").

FOR SHOVEL SKIDDER OPERATIONS.
(See figure 4 on facing page for typical area configuration.)

1. Average setup time = 0.099 hour (mean from 16 shovel skidding operations).
2. Area for setup = 15,000 sq.ft. or 0.344 acre.
3. Combining steps 1 and 2 get 0.29 hour/acre.
4. Average skidding distance = 76 feet.
5. Multiplying results from 3 and 4 get 22, thus y = 22/x (see explanation in step 5 under "FOR HIGH-LEAD, PORTABLE TOWER OPERATIONS").

Ideally, since the maximum skidding distance for shovel skidding is 150 feet, it would seem that each setup covered a semicircular area enclosing 35,350 sq.ft. instead of 15,000 sq.ft. However, in practice figure 4 as sketched shows the typical operating procedure.

FOR ROLLING STOCK SKIDDERS.

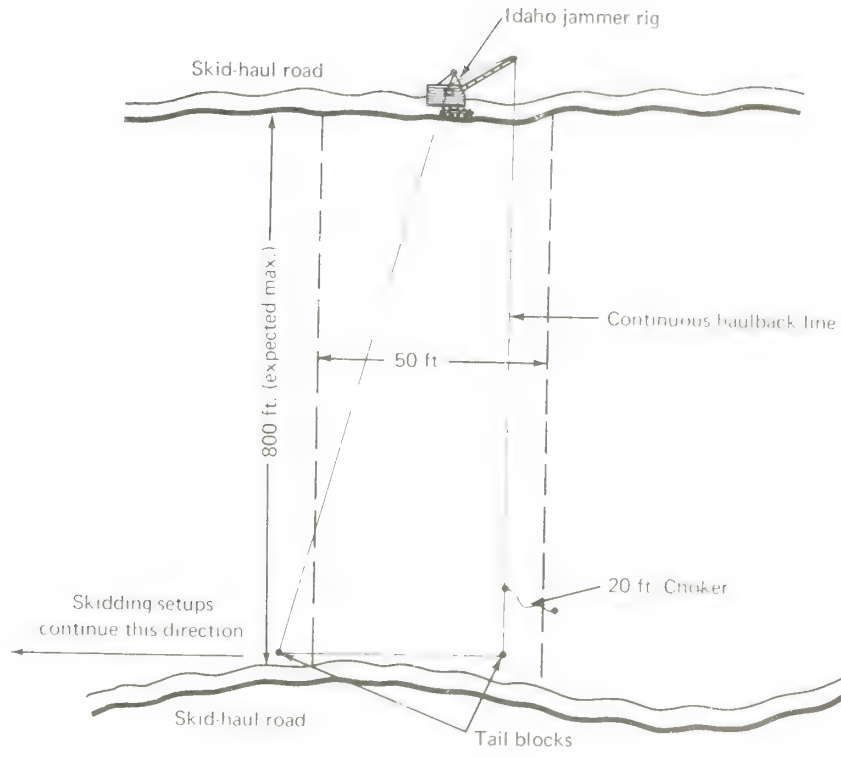
Setup times were not considered for rolling stock skidding operations, which includes such equipment as tracklaying and wheeled skidders. This equipment is used in other operations of the production cycle; namely, traveling unloaded, clearing trails, hooking chokers, freeing chokers, traveling loaded, unhooking chokers, and decking logs. However, "hook chokers" were not included in the production cycle for rolling stock.

$/hour denotes the hourly owning and operating costs normally experienced from equipment service, which includes such items as depreciation (initial cost less salvage value), interest, insurance, taxes, fuel and lubricants, repairs, tires, workmen's compensation, and operator's wages. It is called "COST" in the program. The average hourly owning and operating costs for the skidding operations observed follow:

	$/hour
Crawler tractor, 25-40 DBHP	6.86
Crawler tractor, 41-60 DBHP	8.21
Crawler tractor, 61-80 DBHP	9.97
Crawler tractor, 110-130 DBHP	12.00
Rubber-tired vehicle, 55-80 BHP	6.78
Rubber-tired vehicle, 81-117 BHP	9.85
High-lead, portable tower	18.87
Idaho jammer	16.00
Shovel (w/tongs)	8.36

Roadbuilding costs are made up of the three inputs shown in figure 1 and now described separately.

Figure 3.--Typical configuration for an Idaho jammer.



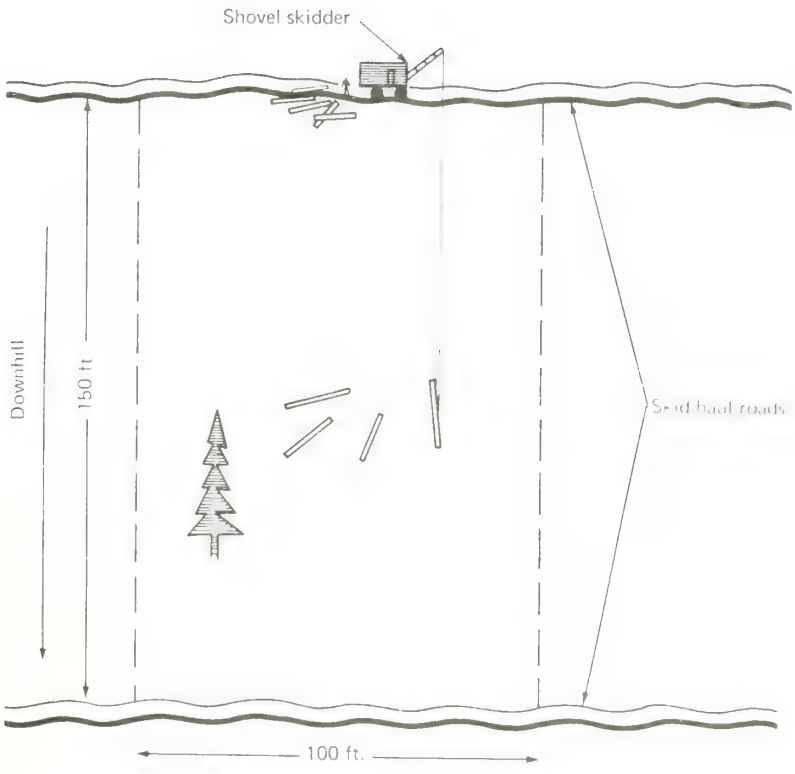


Figure 4.--Typical configuration for a shovel skidder.

ROADBUILDING COSTS

Feet/acre defines the road length in feet to be built for each acre to be skidded as a function of the average skidding distance. It is derived similarly to setup time/acre and introduced into the program as "RDLG." In figure 5 below,

$$x = \frac{1(\text{unit distance}) \times 43{,}560 \text{ (sq.ft./acre)}}{2y \text{ (feet)}}$$

$$x = \frac{20{,}000}{y}$$ (roughly, since the road length equation is the same for all skidding methods)

where x = feet of road length/acre to be skidded
y = average skidding distance.

$/hour represents the roadbuilding cost per hour. Like owning and operating costs, it is the average of all roadbuilding tractor costs observed--$13.58/hour, which is shown in the program as $13.58.

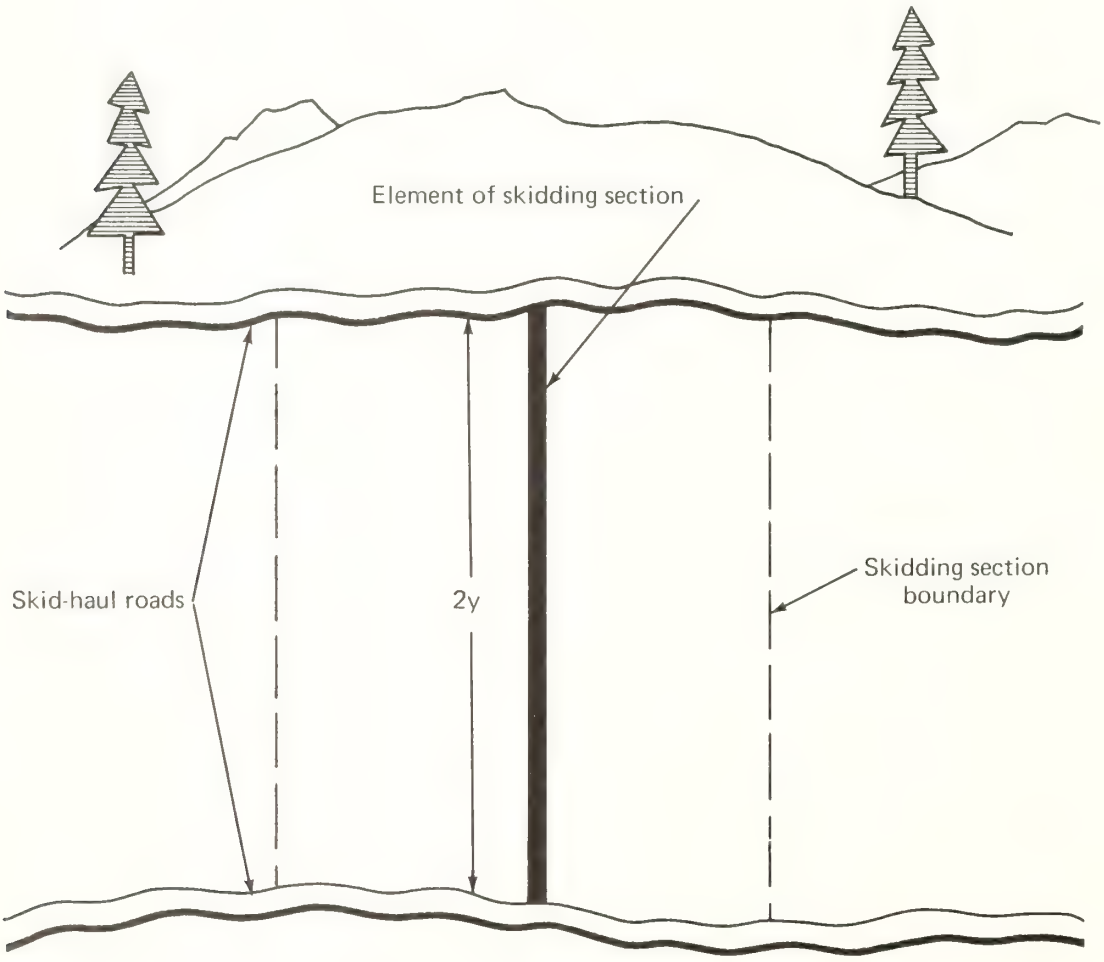


Figure 5.--Typical configuration when building skidding roads.

Feet/hour is the rate for building a skidding road. It appears as hours/feet in the program equation.

Forbes[1] provided the following data on the performance of a typical roadbuilder using crawler tractors:

Performance	Slope	
(Linear feet/hour)	(Degrees)	(Percent)
400	10	17.6
190	20	36.4
110	30	57.7

Using this data, we developed the following quadratic formula for estimating linear feet/hour of road bladed as a function of slope:

$$F = 0.185\,S^2 - 21.155\,S + 715.045$$

where F = linear feet per hour of road bladed
S = percent slope.

The regression equation of feet/hour as a function of slope is found at the end of line 2, statement 35, in the computer program.

[1] Forbes, Reginald D. Forestry handbook, section 18, page 20, table 12. 1,143 pp., illus. New York: The Ronald Press Co. 1961.

COMPUTER PROGRAM

```
      DIMENSION          (T(48),CPMBF(20)
   13 CONTINUE
      J=O
      READ 1,(T(I),I=1,12)
    1 FORMAT (12A4)
    2 FORMAT (1H1,12A4)
      READ 5,K,RC,SC,DC,XLC,COST,DELAY
    5 FORMAT (I10,4F8.6,2F5.2)
      IF(K-1)  3,4,4
    3 GO TO 50
    4 CONTINUE
      READ 10,L,M,N,XXGPC,XETUP,CLC
   10 FORMAT  (9F8.2)
   20 DO 30 II =  5,60,5     MBFPA=II
      PRINT 2,(T(I),I=1,12)
      PUNCH 8,(T(I),I=1,12)
    8 FORMAT (12A4,20X,2H *)
      PRINT 40, MBFPA
   40 FORMAT (/F10.0,29H THOUSAND BOARD FEET PER ACRE)
      PUNCH 6, MBFPA
    6 FORMAT (F10.0,29H THOUSAND BOARD FEET PER ACRE,29X,2H 1)
      PRINT 41
   41 FORMAT(//5X,48H DIST      SLOPE      LOGS PER THOUSAND BOARD FEET)
      PUNCH 9
    9 FORMAT(   5X,48H DIST      SLOPE      LOGS PER THOUSAND BOARD FEET,
     115X,2H 2)
      PRINT 42
   42 FORMAT (25X,43H  4    6    8    10    12    14    16    //)
      PUNCH 7
    7 FORMAT (25X,45H  4    6    8    10    12    14    16     2)
      DO 30  IXX=L,M,N
      DIST=IXX
      RDLG=20000./DIST
      SETUP=XETUP/DIST
      PRINT 51
   51 FORMAT(/)
      PUNCH 21
   21 FORMAT(68X,2H 1)
      DO 30 IXXX = 5,40, 5
      SLOPE=IXXX
      XLGPC=XXGPC
      DO 35  IX=4,16,2
      LGPMBF=IX
      XLGPC=XLGPC+CLC
      IF (XLGPC-16.) 26,26,25
   25 XLGPC=16.
   26 CONTINUE
      J=J+1
      XGPMBF=LGPMBF
      XBFPA=MBFPA
   35 CPMBF(J)= ((XGPMBF*XBFPA*(RC+(SC*SLOPE)+(DC*DIST)+XLC*XLGPC))
      1*(1.+DELAY)/
      2XLGPC+SETUP)*COST+RDLG*(13.58/((.185*SLOPE**2)-(21.155*SLOPE)
      3+715.045)))/XBFPA
      PRINT 32, DIST,SLOPE,(CPMBF(JJ),JJ=1,J)
      PUNCH 32, DIST,SLOPE,(CPMBF(JJ),JJ=1,J)
   32 FORMAT(F10.0,F7.0,6X,7F6.2)
      J=O
   30 CONTINUE
      GO to 13
   50 CALL EXIT
      END
```

Table 1.--Operating costs using 25-40 DBHP crawler tractors for three different stand densities commonly found in Montana, Idaho, and northwestern Wyoming

Distance (feet)	Slope (percent)	5 THOUSAND BOARD FEET PER ACRE							10 THOUSAND BOARD FEET PER ACRE							15 THOUSAND BOARD FEET PER ACRE						
		Logs/M bd.ft.							Logs/M bd.ft.							Logs/M bd.ft.						
		4	6	8	10	12	14	16	4	6	8	10	12	14	16	4	6	8	10	12	14	16
		Dollars/M bd ft							*Dollars/M bd ft*							*Dollars/M bd.ft.*						
200	5	2.99	3 62	4.17	4.67	5.14	5.61	6 06	2.77	3 40	3.95	4 45	4 92	5.38	5 83	2.70	3.33	3.87	4.37	4.85	5.31	5 76
200	10	3.27	3.92	4.48	4.99	5.47	5.94	6 39	3.01	3.66	4.22	4.73	5.21	5.68	6.13	2.92	3.57	4.13	4 64	5.12	5.59	6 04
200	15	3.56	4 24	4.81	5.33	5.82	6.29	6 75	3.25	3.93	4.50	5.02	5.51	5.98	6.44	3.15	3.82	4.40	4.92	5.41	5 88	6.34
200	20	3.88	4 58	5.17	5.70	6.19	6 67	7.13	3.50	4.21	4.79	5.32	5.82	6 30	6 76	3.38	4.08	4 67	5 20	5.70	6 17	6 64
200	25	4.23	4.95	5.56	6.10	6 60	7.08	7 55	3.78	4.50	5.11	5.65	6.15	6.63	7 10	3.63	4.35	4.96	5.50	6.00	6.48	6.95
200	30	4.62	5.37	5 99	6.54	7.05	7.53	8 00	4.07	4.82	5.44	5 99	6.50	6 98	7.45	3.89	4.64	5.26	5.80	6.31	6.80	7.27
200	35	5.06	5 84	6.47	7.03	7.55	8.04	8 51	4.39	5.16	5.80	6.35	6.87	7.36	7.84	4.16	4.94	5.57	6.13	6.65	7.14	7.61
200	40	5.56	6 36	7.00	7.57	8 09	8.59	9 07	4.73	5.53	6.18	6.75	7.27	7.77	8.25	4.46	5 26	5.90	6.47	7.00	7.49	7 97
300	5	3 20	3 88	4 45	4.97	5.46	5.93	6 39	3.06	3.73	4.30	4.82	5.31	5.78	6.24	3.01	3 68	4.25	4.77	5.26	5.73	6.19
300	10	3 45	4.15	4.74	5 26	5.76	6.23	6 70	3.28	3.98	4.56	5.09	5.59	6 06	6.52	3.22	3 92	4.50	5.03	5.53	6 00	6 46
300	15	3.71	4.43	5 03	5.57	6.07	6.55	7 02	3.50	4.23	4.83	5.36	5.87	6.35	6.81	3.43	4.16	4.76	5.30	5 80	6 28	6.74
300	20	3.99	4 73	5 35	5.90	6.41	6.89	7 36	3.74	4 49	5.10	5 65	6.16	6.64	7.11	3 66	4.40	5 02	5 57	6.08	6.56	7.03
300	25	4 29	5 06	5.69	6.24	6.76	7.25	7 72	3.99	4.76	5.39	5.94	6.46	6.95	7.42	3.89	4.66	5.29	5.84	6.36	6 85	7.32
300	30	4 61	5 41	6 05	6.62	7.14	7.64	8 12	4.25	5.04	5.69	6 25	6.78	7.27	7.75	4.12	4.92	5.56	6.13	6 65	7.15	7.63
300	35	4.97	5.79	6 45	7.03	7.56	8.06	8 54	4.52	5.34	6 00	6.58	7.11	7.61	8.00	4.37	5.19	5 85	6.43	6.96	7.46	7 94
300	40	5.36	6.21	6.88	7.47	8.01	8 51	9 00	4.82	5.66	6.33	6.92	7 46	7.96	8.45	4.63	5.48	6.15	6.74	7.27	7.78	8.27
400	5	3.49	4.21	4.81	5.34	5.84	6.32	6 79	3.38	4.10	4.70	5.23	5.73	6.21	6 68	3.34	4.06	4.66	5.20	5.70	6.18	6.64
400	10	3 72	4.47	5.08	5 62	6.13	6.62	7 09	3.59	4 34	4.95	5.49	6.00	6 49	6 96	3.55	4.29	4.90	5.45	5.96	6.44	6 91
400	15	3.96	4.73	5.36	5 92	6.43	6.92	7 39	3.81	4.58	5.21	5.76	6.28	6.77	7.24	3.76	4.53	5.15	5.71	6 22	6.71	7.19
400	20	4.22	5.01	5.65	6.22	6.74	7.24	7 71	4.04	4.83	5.47	6.03	6.56	7.05	7.53	3.97	4 77	5.41	5 97	6 49	6.99	7 47
400	25	4.49	5 31	5.97	6.54	7.07	7.57	8 05	4.27	5.09	5.74	6.32	6 85	7.35	7.83	4.19	5.01	5 67	6.24	6 77	7.27	7.75
400	30	4.79	5.63	6.30	6.88	7.42	7 92	8 41	4.51	5.35	6.02	6.61	7.14	7.65	8.14	4.42	5.26	5.93	6.52	7.05	7 56	8.04
400	35	5.11	5.97	6.66	7.25	7.79	8.30	8 79	4.77	5.63	6.32	6.91	7.46	7.97	8 46	4 66	5 52	6 21	6 80	7.34	7.85	8.34
400	40	5.45	6.34	7 04	7.64	8.19	8.71	9 20	5 04	5.93	6.63	7.23	7.78	8.30	8.79	4.90	5.79	6.49	7.09	7.64	8 16	8.65
500	5	3.80	4.57	5.19	5.75	6.26	6 75	7 22	3.71	4.48	5.10	5.66	6 17	6.66	7.13	3.69	4 45	5.07	5.63	6.14	6.63	7.10
500	10	4 03	4.82	5 46	6.02	6.54	7 04	7 51	3.92	4.71	5.35	5 92	6.44	6 93	7.41	3.89	4 68	5.32	5 88	6.40	6 90	7 37
500	15	4.26	5.07	5 73	6.30	6.83	7.33	7 81	4.14	4.95	5.60	6.18	6.71	7.21	7.69	4 10	4.91	5.56	6.14	6 66	7.16	7.65
500	20	4.50	5 34	6 01	6.59	7.13	7.63	8 12	4.36	5.19	5.86	6 44	6.98	7.48	7.97	4.31	5.14	5.81	6.40	6 93	7.44	7.92
500	25	4 76	5.62	6 31	6.90	7.44	7.95	8 44	4.58	5.44	6.13	6.72	7.26	7.77	8 26	4.52	5.38	6.07	6 66	7.20	7.71	8 20
500	30	5 04	5 92	6.62	7.22	7.77	8 29	8 78	4.82	5.70	6.40	7.00	7.55	8.07	8.56	4.74	5.63	6.32	6.93	7.48	7.99	8.48
500	35	5 33	6 24	6 95	7.56	8.12	8 64	9 14	5.06	5.97	6.68	7.29	7.85	8.37	8 87	4.97	5.88	6.59	7 20	7.76	8 28	8.78
500	40	5.64	6 58	7.30	7.92	8.49	9 01	9 51	5.31	6.25	6.97	7.59	8.16	8 68	9.18	5.20	6.14	6 86	7.49	8 05	8.57	9 07
600	5	4 13	4.94	5 59	6.16	6 69	7.19	7 67	4.06	4 87	5.52	6.09	6.62	7.12	7 60	4.03	4.84	5.49	6.07	6.59	7.09	7.57
600	10	4 35	5.19	5.85	6.43	6.97	7.47	7 96	4.27	5.10	5.76	6.35	6.88	7.38	7.87	4.24	5.07	5.74	6 32	6 85	7.36	7 84
600	15	4 58	5 44	6 12	6.71	7 25	7.76	8 25	4.48	5.33	6.01	6.61	7.15	7.66	8.14	4.44	5.30	5.98	6.57	7.11	7.62	8 11
600	20	4 81	5.70	6.39	6 99	7.54	8.05	8 55	4 69	5.57	6.27	6 87	7.42	7.93	8.42	4.65	5 53	6.23	6.83	7.37	7 89	8.38
600	25	5.06	5 97	6 68	7.29	7.84	8.36	8 86	4.91	5.82	6.53	7.14	7 69	8.21	8.71	4.86	5.77	6 48	7.09	7.64	8.16	8 66
600	30	5.32	6.25	6 97	7 60	8.16	8.68	9 18	5.14	6 07	6.79	7.41	7.97	8.50	9.00	5.08	6 01	6 73	7.35	7.91	8 44	8.94
600	35	5 60	6.55	7 29	7.92	8.49	9.02	9 52	5.37	6 33	7 07	7.70	8 26	8.79	9 30	5.30	6 25	6 99	7.62	8.19	8.72	9.22
600	40	5 89	6.87	7 62	8.26	8 84	9 37	9 88	5 62	6 59	7.35	7.99	8 56	9.10	9 61	5 52	6 50	7 26	7 90	8.47	9.01	9 52

Table 2.--Operating costs using 41-60 DBHP crawler tractors for three different stand densities commonly found in Montana, Idaho, and northwestern Wyoming

Distance (feet)	Slope (percent)	5 THOUSAND BOARD FEET PER ACRE							10 THOUSAND BOARD FEET PER ACRE							15 THOUSAND BOARD FEET PER ACRE						
		Logs/M bd.ft.							Logs/M bd.ft.							Logs/M bd.ft.						
		4	6	8	10	12	14	16	4	6	8	10	12	14	16	4	6	8	10	12	14	16
		Dollars/M bd.ft.							Dollars/M bd.ft.							Dollars/M bd.ft.						
200	5	2.86	3.50	4.07	4.60	5.11	5.60	6.09	2.63	3.28	3.85	4.38	4.89	5.38	5.87	2.56	3.20	3.77	4.30	4.81	5.31	5.79
200	10	3.08	3.74	4.32	4.86	5.37	5.87	6.36	2.82	3.48	4.06	4.60	5.11	5.61	6.10	2.73	3.39	3.97	4.51	5.02	5.52	6.01
200	15	3.32	4.00	4.59	5.13	5.65	6.16	6.65	3.01	3.69	4.28	4.82	5.34	5.85	6.34	2.91	3.59	4.18	4.72	5.24	5.74	6.24
200	20	3.59	4.28	4.88	5.44	5.96	6.47	6.96	3.21	3.91	4.51	5.06	5.59	6.10	6.59	3.09	3.79	4.39	4.94	5.47	5.97	6.47
200	25	3.89	4.60	5.21	5.77	6.30	6.81	7.31	3.44	4.15	4.76	5.32	5.85	6.36	6.86	3.29	4.00	4.61	5.17	5.70	6.21	6.71
200	30	4.23	4.96	5.59	6.15	6.69	7.20	7.70	3.68	4.41	5.04	5.60	6.14	6.65	7.15	3.50	4.23	4.85	5.42	5.95	6.47	6.97
200	35	4.62	5.37	6.01	6.58	7.12	7.64	8.14	3.95	4.70	5.33	5.91	6.45	6.96	7.47	3.72	4.47	5.11	5.68	6.22	6.74	7.24
200	40	5.06	5.83	6.48	7.06	7.60	8.13	8.63	4.24	5.01	5.65	6.23	6.78	7.30	7.81	3.97	4.74	5.38	5.96	6.50	7.03	7.53
300	5	2.84	3.50	4.08	4.61	5.13	5.63	6.12	2.69	3.35	3.93	4.47	4.98	5.48	5.97	2.64	3.30	3.88	4.42	4.93	5.43	5.92
300	10	3.03	3.71	4.30	4.84	5.36	5.87	6.36	2.86	3.54	4.13	4.67	5.19	5.69	6.19	2.80	3.48	4.07	4.61	5.13	5.64	6.13
300	15	3.24	3.94	4.54	5.09	5.61	6.12	6.62	3.04	3.73	4.33	4.88	5.41	5.91	6.41	2.97	3.66	4.26	4.81	5.34	5.85	6.34
300	20	3.47	4.18	4.79	5.35	5.88	6.39	6.89	3.22	3.93	4.54	5.10	5.63	6.14	6.64	3.14	3.85	4.46	5.02	5.55	6.06	6.56
300	25	3.72	4.45	5.07	5.64	6.17	6.68	7.19	3.42	4.15	4.77	5.34	5.87	6.38	6.89	3.32	4.05	4.67	5.24	5.77	6.28	6.79
300	30	3.99	4.74	5.38	5.95	6.49	7.01	7.51	3.63	4.38	5.01	5.58	6.12	6.64	7.14	3.50	4.25	4.89	5.46	6.00	6.52	7.02
300	35	4.30	5.07	5.71	6.29	6.84	7.36	7.87	3.85	4.62	5.26	5.84	6.39	6.91	7.42	3.70	4.47	5.11	5.69	6.24	6.76	7.27
300	40	4.65	5.43	6.08	6.67	7.22	7.75	8.26	4.10	4.88	5.54	6.12	6.67	7.20	7.71	3.91	4.70	5.35	5.94	6.49	7.01	7.53
400	5	2.89	3.57	4.16	4.70	5.22	5.72	6.22	2.78	3.46	4.05	4.59	5.11	5.61	6.10	2.75	3.42	4.01	4.55	5.07	5.58	6.07
400	10	3.08	3.77	4.37	4.92	5.44	5.95	6.45	2.95	3.64	4.24	4.79	5.31	5.82	6.32	2.90	3.60	4.20	4.75	5.27	5.78	6.27
400	15	3.27	3.98	4.59	5.15	5.68	6.19	6.69	3.11	3.83	4.44	4.99	5.52	6.03	6.53	3.06	3.78	4.38	4.94	5.47	5.98	6.48
400	20	3.47	4.20	4.82	5.39	5.92	6.44	6.94	3.29	4.02	4.64	5.20	5.74	6.25	6.75	3.23	3.96	4.58	5.14	5.68	6.19	6.69
400	25	3.70	4.44	5.08	5.65	6.19	6.70	7.21	3.47	4.22	4.85	5.42	5.96	6.48	6.98	3.40	4.14	4.78	5.35	5.89	6.40	6.91
400	30	3.94	4.71	5.35	5.93	6.47	6.99	7.50	3.67	4.43	5.07	5.65	6.20	6.72	7.22	3.57	4.34	4.98	5.56	6.10	6.63	7.13
400	35	4.21	4.99	5.64	6.23	6.78	7.31	7.82	3.87	4.65	5.31	5.89	6.44	6.97	7.48	3.76	4.54	5.19	5.78	6.33	6.86	7.37
400	40	4.50	5.30	5.97	6.56	7.11	7.64	8.16	4.09	4.89	5.55	6.15	6.70	7.23	7.74	3.95	4.75	5.42	6.01	6.56	7.09	7.61
500	5	2.98	3.67	4.27	4.82	5.34	5.85	6.34	2.89	3.58	4.18	4.73	5.25	5.76	6.26	2.86	3.55	4.15	4.70	5.23	5.73	6.23
500	10	3.15	3.87	4.47	5.03	5.56	6.07	6.57	3.05	3.76	4.37	4.93	5.45	5.96	6.46	3.02	3.73	4.33	4.89	5.42	5.93	6.43
500	15	3.34	4.07	4.68	5.25	5.78	6.30	6.80	3.21	3.94	4.56	5.13	5.66	6.17	6.67	3.17	3.90	4.52	5.08	5.62	6.13	6.63
500	20	3.53	4.28	4.91	5.48	6.02	6.53	7.04	3.38	4.13	4.76	5.33	5.87	6.39	6.89	3.33	4.08	4.71	5.28	5.82	6.34	6.84
500	25	3.74	4.50	5.14	5.72	6.26	6.79	7.29	3.56	4.32	4.96	5.54	6.08	6.61	7.11	3.50	4.26	4.90	5.48	6.02	6.55	7.05
500	30	3.96	4.74	5.39	5.98	6.53	7.05	7.56	3.74	4.52	5.17	5.76	6.31	6.83	7.34	3.67	4.45	5.10	5.69	6.23	6.76	7.27
500	35	4.20	5.00	5.67	6.26	6.81	7.34	7.85	3.93	4.73	5.40	5.99	6.54	7.07	7.58	3.84	4.64	5.31	5.90	6.45	6.98	7.49
500	40	4.47	5.28	5.96	6.56	7.12	7.65	8.16	4.14	4.95	5.63	6.23	6.79	7.32	7.84	4.03	4.84	5.52	6.12	6.68	7.21	7.73
600	5	3.08	3.79	4.40	4.95	5.48	5.99	6.49	3.01	3.72	4.32	4.88	5.41	5.92	6.41	2.98	3.69	4.30	4.86	5.38	5.89	6.39
600	10	3.25	3.98	4.59	5.16	5.69	6.20	6.71	3.16	3.89	4.51	5.07	5.60	6.12	6.62	3.13	3.86	4.48	5.04	5.58	6.09	6.59
600	15	3.43	4.17	4.80	5.37	5.91	6.43	6.93	3.32	4.07	4.70	5.27	5.81	6.32	6.83	3.29	4.03	4.66	5.23	5.77	6.29	6.79
600	20	3.61	4.37	5.01	5.59	6.13	6.66	7.16	3.49	4.25	4.89	5.47	6.01	6.53	7.04	3.45	4.21	4.85	5.43	5.97	6.49	7.00
600	25	3.81	4.59	5.24	5.82	6.37	6.90	7.41	3.66	4.44	5.09	5.67	6.22	6.75	7.26	3.61	4.39	5.04	5.62	6.17	6.70	7.21
600	30	4.02	4.82	5.48	6.07	6.62	7.15	7.66	3.83	4.63	5.29	5.89	6.44	6.97	7.48	3.77	4.57	5.23	5.82	6.38	6.91	7.42
600	35	4.24	5.06	5.73	6.33	6.89	7.42	7.94	4.02	4.83	5.51	6.11	6.66	7.20	7.71	3.94	4.76	5.43	6.03	6.59	7.12	7.64
600	40	4.19	5.32	6.00	6.61	7.17	7.71	8.23	4.21	5.05	5.73	6.34	6.90	7.44	7.95	4.12	4.95	5.64	6.24	6.81	7.34	7.86

Table 3.--Operating costs using 61-80 DBHP crawler tractors for three different stand densities commonly found in Montana, Idaho, and northwestern Wyoming

Distance (feet)	Slope (percent)	5 THOUSAND BOARD FEET PER ACRE							10 THOUSAND BOARD FEET PER ACRE							15 THOUSAND BOARD FEET PER ACRE						
		Logs/M bd.ft.							Logs/M bd.ft.							Logs/M bd.ft.						
		4	6	8	10	12	14	16	4	6	8	10	12	14	16	4	6	8	10	12	14	16
		Dollars/M bd ft							Dollars/M bd ft							Dollars/M bd ft						
200	5	2.44	2.93	3.34	3.73	4.09	4.44	4.80	2.22	2.71	3.12	3.51	3.87	4.22	4.58	2.15	2.63	3.05	3.43	3.79	4.14	4.51
200	10	2.43	2.90	3.31	3.69	4.05	4.40	4.76	2.17	2.64	3.05	3.43	3.79	4.14	4.50	2.08	2.55	2.96	3.34	3.70	4.05	4.41
200	15	2.43	2.90	3.30	3.67	4.03	4.37	4.73	2.12	2.59	2.99	3.36	3.72	4.06	4.42	2.02	2.48	2.89	3.26	3.61	3.96	4.32
200	20	2.46	2.91	3.31	3.68	4.03	4.37	4.73	2.09	2.54	2.94	3.31	3.66	4.00	4.36	1.97	2.42	2.82	3.18	3.54	3.88	4.23
200	25	2.53	2.97	3.36	3.72	4.07	4.41	4.76	2.08	2.52	2.91	3.27	3.62	3.96	4.31	1.93	2.37	2.76	3.12	3.47	3.81	4.16
200	30	2.64	3.06	3.45	3.80	4.15	4.49	4.84	2.09	2.51	2.90	3.25	3.60	3.94	4.29	1.90	2.33	2.71	3.07	3.42	3.75	4.10
200	35	2.79	3.21	3.58	3.94	4.28	4.62	4.96	2.12	2.53	2.91	3.26	3.61	3.94	4.29	1.89	2.31	2.68	3.04	3.38	3.72	4.06
200	40	3.00	3.40	3.77	4.12	4.46	4.79	5.13	2.17	2.58	2.95	3.30	3.64	3.97	4.31	1.90	2.30	2.67	3.02	3.36	3.69	4.03
300	5	2.55	3.06	3.50	3.89	4.26	4.62	5.00	2.40	2.91	3.35	3.74	4.12	4.47	4.85	2.35	2.87	3.30	3.70	4.07	4.42	4.80
300	10	2.50	3.01	3.44	3.83	4.20	4.55	4.92	2.33	2.84	3.26	3.65	4.02	4.38	4.75	2.27	2.78	3.21	3.60	3.97	4.32	4.69
300	15	2.48	2.97	3.39	3.78	4.14	4.49	4.86	2.27	2.76	3.19	3.57	3.94	4.29	4.66	2.20	2.70	3.12	3.50	3.87	4.22	4.59
300	20	2.47	2.95	3.36	3.74	4.11	4.46	4.82	2.22	2.70	3.12	3.50	3.86	4.21	4.57	2.14	2.62	3.03	3.41	3.78	4.13	4.49
300	25	2.48	2.95	3.36	3.73	4.09	4.44	4.80	2.18	2.65	3.06	3.43	3.79	4.14	4.50	2.08	2.55	2.96	3.33	3.69	4.04	4.40
300	30	2.52	2.98	3.38	3.75	4.11	4.45	4.81	2.15	2.61	3.01	3.38	3.74	4.08	4.44	2.03	2.49	2.89	3.26	3.62	3.96	4.32
300	35	2.59	3.04	3.43	3.80	4.15	4.49	4.85	2.14	2.59	2.98	3.35	3.70	4.04	4.40	1.99	2.44	2.83	3.20	3.55	3.89	4.25
300	40	2.70	3.13	3.52	3.88	4.23	4.57	4.92	2.15	2.59	2.97	3.33	3.68	4.02	4.37	1.97	2.40	2.79	3.15	3.50	3.84	4.19
400	5	2.72	3.27	3.72	4.13	4.51	4.88	5.26	2.61	3.16	3.61	4.02	4.40	4.76	5.15	2.57	3.12	3.58	3.98	4.36	4.73	5.11
400	10	2.67	3.20	3.65	4.05	4.43	4.79	5.17	2.54	3.07	3.52	3.92	4.30	4.66	5.04	2.49	3.03	3.48	3.88	4.26	4.62	5.00
400	15	2.62	3.15	3.59	3.99	4.36	4.72	5.10	2.47	2.99	3.43	3.83	4.21	4.57	4.94	2.42	2.94	3.38	3.78	4.15	4.51	4.89
400	20	2.59	3.11	3.54	3.93	4.30	4.66	5.03	2.41	2.92	3.35	3.75	4.12	4.47	4.85	2.35	2.86	3.29	3.69	4.06	4.41	4.79
400	25	2.58	3.08	3.51	3.90	4.26	4.62	4.99	2.35	2.86	3.28	3.67	4.04	4.39	4.76	2.28	2.78	3.21	3.60	3.96	4.32	4.69
400	30	2.59	3.08	3.50	3.88	4.24	4.60	4.96	2.31	2.80	3.22	3.60	3.97	4.32	4.69	2.22	2.71	3.13	3.51	3.88	4.23	4.59
400	35	2.62	3.10	3.51	3.89	4.25	4.60	4.96	2.28	2.76	3.17	3.55	3.91	4.26	4.62	2.17	2.65	3.06	3.44	3.80	4.15	4.51
400	40	2.67	3.14	3.55	3.92	4.28	4.63	4.98	2.26	2.73	3.14	3.51	3.87	4.21	4.57	2.13	2.59	3.00	3.37	3.73	4.08	4.44
500	5	2.93	3.51	3.98	4.40	4.79	5.16	5.55	2.84	3.42	3.89	4.31	4.70	5.07	5.46	2.81	3.39	3.86	4.28	4.67	5.04	5.43
500	10	2.87	3.43	3.90	4.31	4.70	5.07	5.46	2.76	3.33	3.80	4.21	4.60	4.96	5.35	2.73	3.30	3.76	4.18	4.56	4.93	5.32
500	15	2.81	3.37	3.83	4.24	4.62	4.99	5.37	2.69	3.24	3.70	4.11	4.50	4.86	5.25	2.65	3.20	3.66	4.07	4.46	4.82	5.21
500	20	2.77	3.31	3.77	4.17	4.55	4.91	5.30	2.62	3.17	3.62	4.02	4.40	4.77	5.15	2.57	3.12	3.57	3.97	4.35	4.72	5.10
500	25	2.74	3.27	3.72	4.12	4.49	4.86	5.23	2.56	3.09	3.54	3.94	4.31	4.68	5.05	2.50	3.03	3.48	3.88	4.25	4.62	4.99
500	30	2.73	3.25	3.69	4.08	4.46	4.81	5.19	2.51	3.03	3.47	3.86	4.24	4.59	4.97	2.43	2.95	3.39	3.79	4.16	4.52	4.90
500	35	2.73	3.24	3.67	4.07	4.44	4.79	5.16	2.46	2.97	3.40	3.80	4.17	4.52	4.89	2.37	2.88	3.31	3.71	4.08	4.43	4.80
500	40	2.76	3.26	3.68	4.07	4.44	4.79	5.16	2.43	2.93	3.35	3.74	4.11	4.46	4.83	2.32	2.82	3.24	3.63	4.00	4.35	4.72
600	5	3.15	3.76	4.25	4.68	5.08	5.46	5.86	3.07	3.69	4.18	4.61	5.01	5.38	5.79	3.05	3.66	4.15	4.58	4.98	5.36	5.76
600	10	3.08	3.68	4.17	4.59	4.99	5.36	5.76	2.99	3.59	4.08	4.51	4.90	5.28	5.67	2.97	3.56	4.05	4.48	4.87	5.25	5.65
600	15	3.02	3.61	4.09	4.51	4.90	5.27	5.67	2.92	3.51	3.98	4.41	4.80	5.17	5.57	2.88	3.47	3.95	4.37	4.76	5.14	5.53
600	20	2.97	3.55	4.02	4.43	4.82	5.19	5.58	2.85	3.42	3.89	4.31	4.70	5.07	5.46	2.80	3.38	3.85	4.27	4.66	5.03	5.42
600	25	2.93	3.49	3.96	4.37	4.76	5.12	5.51	2.78	3.34	3.81	4.22	4.61	4.97	5.36	2.73	3.29	3.76	4.17	4.56	4.92	5.31
600	30	2.90	3.46	3.91	4.32	4.70	5.07	5.45	2.72	3.27	3.73	4.14	4.52	4.89	5.27	2.66	3.21	3.67	4.08	4.46	4.82	5.21
600	35	2.89	3.43	3.88	4.29	4.67	5.03	5.41	2.67	3.21	3.66	4.06	4.44	4.80	5.19	2.59	3.13	3.58	3.99	4.37	4.73	5.11
600	40	2.90	3.43	3.87	4.27	4.65	5.01	5.39	2.63	3.16	3.60	4.00	4.37	4.73	5.11	2.53	3.06	3.51	3.91	4.28	4.64	5.02

Table 4.--Operating costs using 110-130 DBHP crawler tractors for three different stand densities commonly found in Montana, Idaho, and northwestern Wyoming

Distance (feet)	Slope (percent)	5 THOUSAND BOARD FEET PER ACRE							10 THOUSAND BOARD FEET PER ACRE							15 THOUSAND BOARD FEET PER ACRE						
		Logs/M bd.ft.							Logs/M bd.ft.							Logs/M bd.ft.						
		4	6	8	10	12	14	16	4	6	8	10	12	14	16	4	6	8	10	12	14	16
		Dollars/M bd ft							*Dollars/M bd.ft.*							*Dollars/M bd.ft.*						
200	5	2.39	2.97	3.81	4.66	5.50	6.34	7.19	2.17	2 75	3.59	4.43	5.28	6.12	6.96	2.09	2.67	3.52	4.36	5.20	6.05	6.89
200	10	2.50	3.08	3.94	4.80	5.65	6.51	7.36	2.24	2.82	3.68	4.54	5.39	6.25	7.10	2.15	2.74	3.59	4.45	5.30	6.16	7.02
200	15	2.63	3.22	4.09	4.96	5.82	6 69	7.56	2.32	2 91	3.78	4.65	5.51	6 38	7.25	2.22	2.81	3.67	4.54	5.41	6.28	7.15
200	20	2.79	3.38	4.26	5.14	6 02	6.90	7.78	2.41	3.01	3.89	4.77	5.65	6.53	7.41	2.29	2.89	3.77	4.65	5.53	6.41	7.29
200	25	2.98	3 58	4.47	5.36	6 26	7.15	8.04	2.53	3.13	4.02	4.91	5.81	6.70	7.59	2.38	2.98	3.87	4.76	5.66	6.55	7.44
200	30	3.21	3.81	4.72	5.62	6.53	7.44	8.34	2 66	3.26	4.17	5.07	5.98	6.89	7.79	2.48	3.08	3.98	4.89	5.80	6.70	7.61
200	35	3.49	4.10	5.02	5.94	6 85	7.77	8.69	2.82	3.42	4.34	5.26	6.18	7.10	8.02	2.59	3.20	4.12	5.04	5.95	6.87	7.79
200	40	3.82	4.43	5.37	6.30	7.23	8.16	9.09	3.00	3.61	4.54	5.47	6.40	7.33	8.26	2.73	3.34	4.27	5.20	6.13	7.06	7.99
300	5	2.48	3.09	4.02	4 96	5.89	6 82	7.76	2.33	2.94	3.88	4.81	5 74	6.67	7.61	2.28	2.89	3.83	4.76	5.69	6.63	7.56
300	10	2.56	3.18	4.12	5 07	6.02	6 96	7.91	2.39	3.01	3.95	4.90	5.84	6.79	7.73	2.33	2.95	3.89	4.84	5.78	6.73	7.68
300	15	2.66	3.28	4.24	5.20	6.16	7.11	8.07	2.46	3.08	4.03	4.99	5.95	6.91	7.87	2.39	3.01	3.96	4.92	5.88	6.84	7.80
300	20	2.78	3.40	4.37	5.34	6.31	7.28	8 25	2 53	3.15	4.12	5.10	6.07	7.04	8.01	2.45	3.07	4.04	5.01	5.98	6.95	7.92
300	25	2.92	3.54	4.53	5.51	6 49	7.48	8.46	2.62	3 24	4.23	5.21	6.19	7.18	8.16	2.52	3.14	4.13	5.11	6.09	7.08	8.06
300	30	3.08	3.71	4 71	5.71	6.70	7.70	8.69	2.72	3.35	4.34	5.34	6.33	7.33	8.33	2.59	3.23	4.22	5.22	6.21	7.21	8.20
300	35	3.28	3.92	4.93	5 93	6.94	7.95	8.96	2.83	3.47	4.48	5.48	6.49	7.50	8.51	2.68	3.32	4.33	5.33	6.34	7.35	8.36
300	40	3 51	4.15	5.17	6.19	7 22	8.24	9.26	2.96	3.61	4.63	5.65	6.67	7.69	8.71	2.78	3.42	4.44	5.46	6.48	7.50	8.52
400	5	2.64	3.28	4.31	5.33	6 35	7.38	8.40	2.53	3.17	4.20	5.22	6 24	7.27	8.29	2.50	3.14	4.16	5.18	6.21	7.23	8.25
400	10	2.72	3.36	4.40	5 43	6.47	7.50	8 54	2.59	3.23	4.27	5.30	6.34	7.37	8.41	2 54	3.19	4.22	5.26	6.29	7.33	8.36
400	15	2.80	3.45	4.49	5.54	6.59	7.64	8 69	2.64	3.29	4.34	5.39	6.44	7.48	8.53	2.59	3.24	4.29	5.34	6.38	7.43	8.48
400	20	2.89	3.55	4.61	5.67	6.73	7.79	8.85	2 71	3.36	4.42	5 48	6.54	7.60	8.66	2.65	3.30	4.36	5.42	6.48	7.54	8.60
400	25	3.00	3 66	4.74	5.81	6.88	7.95	9.03	2 78	3.44	4.51	5.58	6.66	7.73	8.80	2.70	3.36	4.44	5.51	6.58	7.65	8.73
400	30	3.14	3.80	4.89	5.97	7.06	8.14	9.23	2 86	3.53	4.61	5.70	6.78	7.87	8.95	2.77	3.43	4.52	5.60	6.69	7.77	8.86
400	35	3.30	3 96	5.06	6.16	7.25	8.35	9.45	2 96	3.62	4.72	5.82	6.92	8.01	9.11	2.85	3.51	4.61	5.71	6.80	7.90	9.00
400	40	3.48	4.15	5 26	6.37	7.48	8 59	9.70	3.07	3.74	4.85	5.96	7.07	8.18	9.29	2.93	3.60	4.71	5.82	6.93	8.04	9.15
500	5	2.84	3.51	4 62	5.73	6.85	7.96	9.07	2.75	3.42	4.53	5.65	6.76	7.87	8.98	2.72	3.39	4.50	5.62	6.73	7.84	8.95
500	10	2.90	3.58	4.70	5.83	6.95	8.08	9.20	2 80	3.47	4 60	5.72	6.85	7.97	9.10	2.76	3.44	4.56	5.69	6.81	7.94	9.06
500	15	2.97	3.65	4 79	5.93	7.07	8.20	9.34	2 85	3.53	4.67	5.81	6.94	8.08	9.22	2.81	3.49	4.63	5.76	6.90	8.04	9.18
500	20	3.06	3.74	4.89	6.04	7.19	8 34	9.49	2.91	3.59	4.74	5.89	7.04	8.19	9.34	2.86	3.54	4.69	5.84	6.99	8.14	9.29
500	25	3.15	3.84	5 00	6.17	7.33	8.49	9.65	2.97	3.66	4.82	5.99	7.15	8.31	9.47	2.91	3.60	4.76	5.93	7.09	8.25	9.41
500	30	3.27	3.96	5.13	6.31	7 18	8 66	9.83	3.05	3 74	4 91	6.09	7.26	8.44	9.61	2.97	3.67	4.84	6.02	7.19	8.36	9.54
500	35	3.40	4.10	5 28	6 47	7.66	8 84	10 03	3.13	3 83	5.01	6.20	7.39	8.57	9.76	3.04	3.74	4.92	6.11	7.30	8.48	9.67
500	40	3.55	4.25	5 45	6 65	7.85	9.05	10.25	3.22	3.92	5.12	6.32	7.52	8.72	9.92	3.11	3.81	5.01	6.21	7.41	8.61	9.81
600	5	3.05	3.75	4.95	6.15	7.36	8.56	9.76	2.97	3.68	4.88	6.08	7.28	8.48	9.69	2.95	3.65	4.85	6.05	7.26	8.46	9.66
600	10	3.11	3 81	5.03	6.24	7.46	8 67	9.88	3 02	3.73	4.94	6.15	7.37	8.58	9.80	2.99	3.70	4.91	6.13	7.34	8.55	9.77
600	15	3.17	3.88	5 11	6.34	7.56	8.79	10.02	3.07	3.78	5.01	6.23	7.46	8.69	9.91	3.04	3.74	4.97	6.20	7.43	8.65	9.88
600	20	3.25	3 96	5.20	6.44	7.68	8.92	10.16	3.12	3.84	5 08	6.32	7.56	8.79	10.03	3.08	3.80	5.04	6.27	7.51	8.75	9.99
600	25	3.33	4.05	5.30	6 55	7.81	9.06	10.31	3.18	3.90	5.15	6.40	7.66	8.91	10.16	3.13	3.85	5.10	6.35	7.61	8.86	10.11
600	30	3.43	4.15	5.42	6 68	7.95	9.21	10.48	3.25	3 97	5.24	6 50	7.76	9.03	10.29	3.19	3.91	5.17	6.44	7.70	8.97	10.23
600	35	3.55	4.28	5.55	6.83	8.11	9.38	10.66	3.32	4.05	5.33	6 60	7.88	9.16	10.43	3.25	3.98	5.25	6.53	7.81	9.08	10.36
600	40	3.68	4.41	5.70	6.99	8 28	9.57	10.86	3.41	4.14	5.43	6.72	8.00	9.29	10.58	3.32	4.05	5.33	6.62	7.91	9.20	10.49

Table 7.--Operating costs using high-lead portable towers for three different stand densities commonly found in Montana, Idaho, and northwestern Wyoming

Distance (feet)	Slope (percent)	5 THOUSAND BOARD FEET PER ACRE							10 THOUSAND BOARD FEET PER ACRE							15 THOUSAND BOARD FEET PER ACRE						
		Logs/M bd.ft.							Logs/M bd.ft.							Logs/M bd.ft.						
		4	6	8	10	12	14	16	4	6	8	10	12	14	16	4	6	8	10	12	14	16
		Dollars/M bd ft							Dollars/M bd ft							Dollars/M bd ft						
200	5	4 09	5 00	5 91	6 82	7 73	8 64	9 55	2 95	[illegible]	4 77	5 68	6 [illegible]	7 [illegible]	8 [illegible]	[illegible]	[illegible]	4 39	5 30	[illegible]	[illegible]	[illegible]
200	10	4 27	5.24	6 20	7 17	8.13	9 10	10 06	3.10	4 06	5.03	5.99	6 96	7 92	8 88	2 71	3 67	4 64	5 60	6 56	7 53	8 49
200	15	4 48	5.50	6 52	7 53	8.55	9.57	10.59	3.26	[illegible]	5 29	6.31	7 33	8 35	9 36	2 85	3 87	4 88	5 90	6 92	[illegible]	8 96
200	20	4 71	5.78	6.86	7.93	9 00	10.07	11 14	3.43	[illegible]	5 57	6 64	7 71	8 79	9 86	3.00	4 07	5 14	6 21	7 29	8 36	9 43
200	25	4 98	6.10	7.23	8 36	9.48	10.61	11.73	3.61	4 74	5 86	6.99	8 12	9 24	10 37	3 16	4 28	5 41	6 53	7 66	8 79	9 91
200	30	5 29	6 47	7.64	8.82	10.00	11.18	12 36	3 82	[illegible]	6 18	7 36	8 54	9.72	10 90	3 33	4 51	5 69	6 87	8 05	9 23	[illegible]
200	35	5 64	6 88	8.11	9.34	10.58	11 81	13.05	4 05	[illegible]	6 52	7.75	8 99	10 22	11.46	3 52	4 76	5 99	7 22	[illegible]	9 69	10 93
200	40	6 05	7.34	8 62	9.91	11.20	12 49	13.77	4.31	[illegible]	6 88	8 17	9 46	10 75	12.04	3 73	5 02	6 30	7 59	8 88	10 17	[illegible]
300	5	3.34	4.25	5 16	6 07	6 99	7 90	8 81	2 58	[illegible]	4 10	5.32	6 23	7 14	8.05	2 33	3 24	4 15	5 06	5 98	6 89	7 80
300	10	3.50	4 46	5 43	6 39	7.36	8.33	9 29	2 71	[illegible]	4 64	5 61	6 58	7 54	8 51	2 45	3 12	4 38	5 35	6 32	7 28	8 25
300	15	3 67	4 69	5.71	6.73	7 75	8.77	9 79	2.85	[illegible]	4.89	5.91	6 93	7 95	8 97	2 58	3 60	4 62	5 64	6 66	7 68	8 70
300	20	3 86	4.93	6 01	7.08	8.16	9.23	10 30	3.00	[illegible]	5.15	6 22	7 30	8.37	9.45	2 72	3 79	4 86	5 94	7 01	8 09	9 16
300	25	4 07	5 20	6 33	7.46	8.58	9 71	10.84	3.16	4 29	5 42	6 55	7 67	8 80	9 93	2 86	3 99	[illegible]	6 24	7 37	8 50	9 63
300	30	4 31	5.50	6 68	7 86	9 04	10.22	11.41	3 34	[illegible]	5.70	6 88	8 06	9 25	10 43	3.01	4 19	5 37	6 56	7 74	8 92	10 10
300	35	4 59	5 82	7.06	8.30	9.53	10.77	12 00	3.53	4 76	6 00	7 24	8 47	9 71	10.94	[illegible]	[illegible]	5 65	6 88	8 12	9 35	[illegible]
300	40	4 89	6 18	7.47	8 76	10 05	11.34	12 63	3 73	[illegible]	6 31	7 60	8 89	10 18	11 47	3 35	4 64	5 93	7 22	8 51	9 80	[illegible]
400	5	2 96	3 88	4 79	5.71	6 62	7.54	8.45	2.39	[illegible]	4.22	5.14	6 05	6 97	7 88	2 20	3 12	4 03	4 95	5 86	6 78	7 69
400	10	3 11	4 08	5 05	6.01	6 98	7 95	8 92	2 52	3 49	4 46	5.43	6 40	7 36	8 33	2 32	3 29	4 26	5 23	6 20	7 17	8 14
400	15	3 26	4.29	5 31	6 33	7.36	8.38	9.40	2 65	[illegible]	4 70	5 72	6 74	7 77	8 79	2 45	3 47	[illegible]	5 52	6 54	7 56	8 58
400	20	3.43	4 51	5 59	6 66	7.74	8.82	9 89	2.79	[illegible]	4 94	6 02	7 10	8 17	[illegible]	2 58	3 65	4 73	5 81	6 88	7 96	9 04
400	25	3 62	4.75	5 88	7.01	8.14	9 27	10 40	2 94	[illegible]	5 20	6 33	7 46	8 59	9 72	2 71	3 84	4 97	6 10	7 23	8 36	9 49
400	30	3.83	5.01	6 20	7 38	8 57	9.75	10 94	3 10	[illegible]	5 47	6 65	7 83	9 02	10 20	2 85	4 04	5 22	6 41	7 59	8 77	9 96
400	35	4 06	5.30	6 54	7.78	9 01	10 25	11.49	3 27	[illegible]	5 74	6 98	8 22	9.46	10 70	3 00	[illegible]	5 48	6 72	7 95	9 19	10 43
400	40	4 32	5 61	6 90	8.19	9.49	10.78	12 07	3.45	4 74	6 03	7.33	8 62	9 91	11 20	3 16	4 45	5 74	7 04	8 33	9 62	10 91
500	5	2.74	3 66	4 57	5 49	6 41	7.32	8.24	2 28	3 20	4.12	5 04	5 95	6 87	7 79	2 13	3 05	3 97	4 88	5 80	6 72	7 64
500	10	2 88	3 85	4.82	5.79	6 76	7.73	8 70	2.41	3.38	4 35	5 32	6 29	7 26	8 23	2 25	3 22	4 19	5 16	6 13	7 11	[illegible]
500	15	3.02	4 05	5.07	6 10	7.12	8.15	9.17	2.53	3 56	4.58	5 61	6 63	7 66	8 68	2 37	3 40	4 42	5 45	6 47	7 50	8 52
500	20	3.18	4 26	5.34	6 42	7 50	8 58	9 66	2 67	3 75	4.83	5 90	6 98	8 06	9 14	2 50	3 57	4 65	5 73	6 81	7 89	8 97
500	25	3.35	4 49	5.62	6 75	7 88	9 02	10.15	2.81	3 94	5 07	6 20	7.34	[illegible]	9 60	2 62	3 76	4 89	6 02	7 16	8 29	9 42
500	30	3.54	4.73	5.91	7.10	8 29	9 47	10.66	2.95	4 14	5 33	6.51	7.70	8 89	10 07	2 76	3 95	5 13	6 32	7 51	8 69	9 88
500	35	3.75	4 99	6 24	7 47	8.71	9.95	11.19	3.11	4 35	5.59	6 83	8 07	9 31	10 56	2 90	4 14	5 38	6 62	7 86	9 10	[illegible]
500	40	3.98	5 27	6 56	7 86	9.15	10 45	11.74	3.28	[illegible]	5 87	7 16	8 46	9 75	[illegible]	3 05	4 34	5 64	6 93	8 23	9 52	[illegible]
600	5	2.59	3.51	4.43	5 35	6.27	7 19	8 11	2 21	3 13	4 05	4 97	5.89	[illegible]	7 73	2 09	3 01	3 93	[illegible]	5 76	6 68	7 60
600	10	2.73	3 70	4.67	5 65	6 62	7.59	8.57	2 33	3 31	4 28	5.25	6 23	7 20	8 17	2 20	3 18	[illegible]	5 12	6 10	7 07	8 04
600	15	2.87	3 89	4.92	5 95	6 97	8 00	9.03	2 46	[illegible]	4 51	5 54	6 57	7 59	8 62	2 32	3 35	4 38	5 40	6 43	7 46	8 49
600	20	3.01	4.10	5.18	6 26	7.34	8 42	9 50	2 59	3 67	4.75	[illegible]	6 91	7 99	9 07	[illegible]	3 52	4 61	5 69	6 77	7 85	[illegible]
600	25	3.18	4 31	5 45	6 58	7.72	8 85	9 99	2 72	3 86	4.99	6 13	7 26	8.40	9 53	2 57	3 70	4 84	5 97	7 11	8 24	9 38
600	30	3.35	4.54	5.73	6 92	8.11	9 29	10.48	2 86	[illegible]	5 24	6 43	7 62	8 81	9 99	2 70	3 89	5 08	6 27	7 45	8 64	9 83
600	35	3 51	4 78	6 03	7 27	8.51	9 75	11.00	3 01	4 25	5 50	6 74	7 98	9 22	10 47	[illegible]	[illegible]	5 32	6 56	7 81	9 05	10 29
600	40	3 75	5.04	6 34	7 64	8 93	10 23	11 53	3 17	4 46	5 76	7 06	8 35	9 65	10 95	2 97	4 27	5 57	6 86	8 16	[illegible]	[illegible]

Table 8.--Operating costs using Idaho jammers for three different stand densities commonly found in Montana, Idaho, and northwestern Wyoming

Distance (feet)	Slope (percent)	5 THOUSAND BOARD FEET PER ACRE							10 THOUSAND BOARD FEET PER ACRE							15 THOUSAND BOARD FEET PER ACRE						
		Logs/M bd.ft.							Logs/M bd.ft.							Logs/M bd.ft.						
		4	6	8	10	12	14	16	4	6	8	10	12	14	16	4	6	8	10	12	14	16
		Dollars/M bd. ft							*Dollars/M bd. ft.*							*Dollars/M bd. ft.*						
100	5	8.44	8.84	9.25	9.65	10.06	10.46	10.86	4.62	5.03	5.43	5.83	6.24	6.64	7.04	3.35	3.75	4.16	4.56	4.96	5.37	5.77
100	10	8.66	9.09	9.52	9.96	10.39	10.83	11.26	4.76	5.19	5.63	6.06	6.50	6.93	7.37	3.46	3.90	4.33	4.76	5.20	5.63	6.07
100	15	8.91	9 38	9.84	10.31	10.77	11.24	11.70	4.92	5.38	5.85	6.31	6.78	7.24	7.71	3.59	4.05	4.52	4.98	5.45	5.91	6.37
100	20	9.22	9.72	10.21	10.71	11.20	11.70	12.19	5.10	5.60	6.09	6.59	7.08	7.58	8.07	3.73	4.23	4.72	5.22	5.71	6.21	6.70
100	25	9.60	10.12	10.65	11.17	11.70	12.22	12.75	5.32	5.85	6.37	6.90	7.42	7.95	8.47	3.90	4.42	4.95	5.47	6.00	6.52	7.05
100	30	10.06	10.61	11.17	11.73	12.28	12.84	13.39	5.58	6.14	6.69	7.25	7.81	8.36	8.92	4.09	4.65	5.20	5.76	6.31	6.87	7.42
100	35	10.62	11.20	11.79	12.38	12.96	13.55	14.13	5.89	6.48	7.06	7.65	8.24	8.82	9.41	4.32	4.90	5.49	6.08	6.66	7.25	7.83
100	40	11.28	11.89	12.51	13.12	13.74	14.36	14.97	6.25	6.87	7.48	8.10	8.72	9.33	9.95	4.58	5.19	5.81	6.43	7.04	7.66	8.28
200	5	4.97	5.55	6.14	6.72	7.30	7.88	8.46	3.07	3.65	4.23	4.81	5.39	5.97	6.55	2.43	3.01	3.59	4.17	4.75	5.33	5.91
200	10	5.11	5.72	6.33	6.95	7.56	8.17	8.78	3.16	3.78	4.39	5.00	5.61	6.22	6.83	2.52	3.13	3.74	4.35	4.96	5.57	6.18
200	15	5.27	5.91	6.55	7.20	7.84	8.48	9.12	3.27	3.92	4.56	5.20	5.84	6.48	7.12	2.61	3.25	3.89	4.53	5.17	5.82	6.46
200	20	5.46	6.13	6.80	7.47	8.14	8.81	9.49	3.40	4.07	4.74	5.41	6.08	6.76	7.43	2.71	3.38	4.05	4.73	5.40	6.07	6.74
200	25	5.67	6.38	7.08	7.78	8.48	9.18	9.89	3.54	4.24	4.94	5.64	6.34	7.05	7.75	2.82	3.53	4.23	4.93	5.63	6.33	7.04
200	30	5.94	6.67	7.40	8.13	8.86	9.60	10.33	3.70	4.43	5.16	5.89	6.63	7.36	8.09	2.95	3.68	4.42	5.15	5.88	6.61	7.35
200	35	6.25	7.01	7.77	8.53	9.30	10.06	10.82	3.88	4.65	5.41	6.17	6.93	7.70	8.46	3.10	3.86	4.62	5.38	6.15	6.91	7.67
200	40	6 60	7.40	8.19	8.98	9.78	10.57	11.36	4.09	4.89	5.68	6.47	7.27	8.06	8.85	3.26	4.05	4.84	5.63	6.43	7.22	8.01
300	5	4 05	4.81	5.57	6.33	7.08	7.84	8.60	2.78	3.54	4.30	5.05	5.81	6.57	7.33	2.36	3.12	3.87	4.63	5.39	6.14	6.90
300	10	4 17	4.96	5.74	6.53	7.32	8.11	8.89	2.87	3.66	4.44	5.23	6.02	6.81	7.59	2.44	3.22	4.01	4.80	5.59	6.37	7.16
300	15	4.29	5.11	5.93	6.75	7.57	8.38	9.20	2.96	3.78	4.60	5.42	6.23	7.05	7.87	2.52	3.34	4.15	4.97	5.79	6.61	7.43
300	20	4.44	5.29	6.13	6.98	7.83	8.68	9.53	3.06	3.91	4.76	5.61	6.46	7.31	8.15	2.61	3.45	4.30	5.15	6.00	6.85	7.70
300	25	4.60	5.48	6.36	7.24	8.12	9.00	9.87	3.18	4.06	4.93	5.81	6.69	7.57	8.45	2.70	3.58	4.46	5.34	6.22	7.10	7.97
300	30	4.80	5.71	6.61	7.52	8.43	9.34	10.25	3.30	4.21	5.12	6.03	6.94	7.85	8.76	2.81	3.72	4.63	5.53	6.44	7.35	8.26
300	35	5.02	5.96	6.90	7.84	8.78	9.72	10.66	3.45	4.39	5.33	6.27	7.21	8.15	9.08	2.92	3.86	4.80	5.74	6.68	7.62	8.56
300	40	5.28	6.25	7.22	8.19	9.16	10.13	11.10	3.61	4.58	5.55	6.52	7.49	8.46	9.43	3.05	4.02	4.99	5.96	6.93	7.90	8.87
400	5	3.77	4.71	5.64	6.57	7.51	8.44	9.37	2.82	3.75	4.68	5.62	6.55	7.49	8.42	2.50	3.43	4.37	5.30	6.23	7.17	8.10
400	10	3.87	4.84	5.80	6.76	7.73	8.69	9.66	2.90	3.86	4.83	5.79	6.75	7.72	8.68	2.57	3.54	4.50	5.47	6.43	7.39	8.36
400	15	3.98	4.98	5.97	6.96	7.96	8.95	9.95	2.98	3.98	4.97	5.97	6.96	7.96	8.95	2.65	3.64	4.64	5.63	6.63	7.62	8.62
400	20	4.10	5.13	6.15	7.18	8.20	9.23	10.25	3.07	4.10	5.12	6.15	7.17	8.20	9.22	2.73	3.76	4.78	5.81	6.83	7.86	8.88
400	25	4.24	5.30	6.35	7.41	8.46	9.52	10.57	3.17	4.23	5.28	6.34	7.40	8.45	9.51	2.82	3.87	4.93	5.98	7.04	8.09	9.15
400	30	4.40	5.49	6.58	7.66	8.75	9.83	10.92	3.29	4.37	5.46	6.54	7.63	8.71	9.80	2.91	4.00	5.08	6.17	7.25	8.34	9.43
400	35	4.59	5.71	6.82	7.94	9.05	10.17	11.29	3.41	4.52	5.64	6.76	7.87	8.99	10.10	3.01	4.13	5.25	6.36	7.48	8.59	9.71
400	40	4.80	5.95	7.09	8.24	9.38	10.53	11.68	3.54	4.69	5.84	6.98	8.13	9.28	10.42	3.12	4.27	5.42	6.56	7.71	8.86	10.00

Table 5.--Operating costs using 55-80 BHP rubber-tired vehicles for three different stand densities commonly found in Montana, Idaho, and northwestern Wyoming

Distance (feet)	Slope (percent)	5 THOUSAND BOARD FEET PER ACRE							10 THOUSAND BOARD FEET PER ACRE							15 THOUSAND BOARD FEET PER ACRE						
		Logs/M bd.ft.							Logs/M bd.ft.							Logs/M bd.ft.						
		4	6	8	10	12	14	16	4	6	8	10	12	14	16	4	6	8	10	12	14	16
		Dollars/M bd ft							Dollars/M bd ft							Dollars/M bd ft						
200	5	1.85	2 27	2 65	3 02	3.37	3.71	4.05	1 63	[illegible]	2 43	2.79	3.15	3 49	3 83	1 56	1.98	2 36	2 72	3 07	3 42	3 76
200	10	1.88	2.29	2 67	3.03	3.38	3.72	4.06	1.62	[illegible]	2.41	2.77	3.12	3.46	3 80	1.53	1.94	2 32	2 68	3 03	3 37	3 71
200	15	1.92	2.33	2.70	3 06	3.41	3.75	4 08	1.61	[illegible]	2.39	2.75	3.10	3.44	3 78	1.51	1 91	2 29	2 65	2 99	3 33	3 67
200	20	1.99	2.39	2.76	3.11	3 46	3.80	4.14	1 62	[illegible]	2.39	2.74	3.09	3 43	3.77	1.50	1 90	2 27	2 62	2 97	3 31	3 64
200	25	2.10	2.49	2.85	3.21	3.55	3 89	4.22	1 65	[illegible]	2.40	2.76	3.10	3.44	3.77	1 50	1 89	2 25	2 61	2 95	3 29	3 62
200	30	2.24	2 63	2 99	3.34	3 68	4.02	4 35	1 69	[illegible]	2.44	2.79	3.13	3.47	3.80	1.51	1 90	2 26	2 61	2 95	3 28	3 62
200	35	2.44	2.82	3.18	3.52	3.86	4.20	4.53	1.76	[illegible]	2.50	2.85	3 19	3.52	3 86	1.54	1.92	2 28	2 62	2 96	3.30	3 63
200	40	2.68	3.06	3 41	3.75	4.09	4 43	4.76	1.86	[illegible]	2.59	2.93	3 27	3 60	3 93	1 58	1 96	2 31	2 65	2 99	3 33	3 66
300	5	2.03	2 49	2 89	3.27	3 64	3.99	4.34	1.88	2 34	2 75	3.12	3.49	3 84	4.19	1.83	2.29	2 70	3 08	3 44	3 79	4 14
300	10	2 03	2 48	2.88	3 26	3.62	3.97	4.32	1.85	2 31	2.71	3.08	3.45	3 80	4.14	1.79	2 25	2 65	3 03	3 39	3 74	4 08
300	15	2.04	2 48	2 88	3 26	3.61	3.97	4.31	1.83	2 28	2 68	3.05	3.41	3.76	4.10	1 76	2 21	2 61	2 98	3.34	3 69	4 04
300	20	2.07	2.51	2 90	3.27	3.63	3 98	4.32	1.82	2 26	2 65	3 02	3.38	3.73	4.07	1 74	2.18	2 57	2 94	3 30	3 65	3 99
300	25	2.12	2 55	2.94	3.31	3.67	4.01	4.36	1.82	[illegible]	2.64	3 01	3.37	3.71	4.06	1.72	2.15	2.54	2 91	3 27	3 61	3 96
300	30	2.20	2.63	3.01	3 38	3.73	4.08	4.42	1.83	[illegible]	2.64	3.01	3.36	3 71	4.05	1.71	2.14	2 52	2 89	3 24	3 59	3 93
300	35	2.31	2 73	3.11	3 48	3.83	4.17	4.51	1.86	[illegible]	2.66	3.03	3.38	3.72	4 06	1 71	2.13	2 51	2 88	3 23	3 57	3 91
300	40	2.46	2.87	3.25	3 61	3 96	4.30	4.64	1.91	2 32	2.70	3 06	3.41	3 75	4 09	1.72	2.14	2 52	2 88	3 23	3 57	3 91
400	5	2.28	2.78	3.21	3 60	3.98	4.34	4.69	2.17	[illegible]	3.10	3.49	3 87	4.23	4 58	2.13	2 63	3 06	3 46	3.83	[illegible]	4 55
400	10	2.26	2 76	3.18	3 57	3.95	4.31	4.66	2.13	[illegible]	3.05	3.44	3 82	4.18	4 53	2.09	2 58	3 01	3 40	3 77	4 13	4 49
400	15	2.26	2.75	3.17	3.56	3.93	4.29	4.64	2.10	[illegible]	3.01	3.40	3.77	4.13	4 48	[illegible]	2.54	2 96	3 35	3.72	4 08	4 43
400	20	2.27	2.75	3.17	3 55	3.92	4.28	4.63	2.08	[illegible]	2.98	3.37	3.74	4.09	4 44	2.02	2.50	2 92	3 30	3 67	4 03	4 38
400	25	2 29	2.77	3.18	3 56	3.93	4.29	4.64	2.07	2 54	2 96	3.34	3 71	4.06	4 41	1 99	2.47	2 88	3 26	3.63	3 99	4 34
400	30	2.34	2 81	3.22	3 60	3.96	4.32	4.67	2.06	[illegible]	2.94	3.32	3 69	4.04	4.39	1.97	2 44	2 85	3.23	3 60	3 95	4.30
400	35	2.41	2.87	3 28	3 66	4.02	4.37	4.72	2.07	[illegible]	2 94	3.32	3 68	4 03	4 38	1 96	2.42	2 83	3 21	3.57	3 92	4 27
400	40	2.51	2 96	3.36	3.74	4.10	4.45	4.80	2.09	2 55	2.95	3.33	3.69	4 04	4.38	1.96	2 41	2 81	3 19	3 55	3 90	4 25
500	5	2.56	3.10	3.55	3 96	4.35	4.72	5.08	2.47	3 01	3 46	3.87	4 26	4.63	4 99	2 44	2 98	3 43	3.84	4 23	4 60	[illegible]
500	10	2 53	3.07	3 52	3.93	4.31	4.68	5 04	2.43	[illegible]	3.41	3.82	4.21	4.58	4 94	2 40	2.93	3 38	3 79	4.17	4.54	[illegible]
500	15	2.52	3.05	3 49	3.90	4 28	4.65	5.01	2.40	[illegible]	3.37	3 78	4.16	4.53	4 88	2 36	2 88	3 33	3.73	4.12	4 48	[illegible]
500	20	2.52	3.04	3.48	3.88	4.26	4.63	4.99	2.37	[illegible]	3.33	3.73	4.11	4.48	4.84	2.32	2 84	3 28	3 68	4 06	4 43	4 79
500	25	2.53	3.04	3 48	3.88	4.26	4.62	4 98	2.35	[illegible]	3.30	3.70	4.08	4.44	4 80	2 29	2 80	3 24	3 64	4 02	4.38	4.74
500	30	2.55	3.06	3.49	3 89	4.27	4.63	4.99	2.33	2 84	3.27	3.67	4 05	4.41	4.77	2.26	2 77	3 20	3 60	3 98	4.34	4 69
500	35	2.60	3.10	3.53	3.92	4.30	4.66	5.02	2.33	[illegible]	3 26	3.65	4.03	4 39	4 75	2 24	2.74	3 17	3 56	3 94	4 30	[illegible]
500	40	2.66	3 16	3.59	3 98	4 35	4.71	5 06	2.33	2 83	3.26	3 65	4 02	4 38	4.73	2.23	2 72	3.15	3.54	3.91	4 27	[illegible]
600	5	2 85	3.43	3 91	4 34	4 74	5.11	5.48	2.78	[illegible]	3.84	4.26	4 66	5.04	5 41	2 75	3.33	3.81	4 24	4.64	5 02	5 38
600	10	2.82	3.40	3.87	4.30	4 69	5.07	5 44	2.74	[illegible]	3.79	4 21	4.61	4.98	5.35	2.71	3.28	3.76	4.18	4.58	4 95	5 32
600	15	2.80	3.37	3.84	4 26	4.66	5 03	5 40	2.70	[illegible]	3.74	4.16	4 55	4.93	5 29	2 66	3 23	3.70	4.13	4.52	4 90	5 26
600	20	2.79	3.35	3 82	4 24	4.63	5.00	5.37	2.67	[illegible]	3.69	4 11	4.51	4 88	5 24	2 63	3 19	3 65	4 07	4.46	4 84	5 20
600	25	2.79	3.34	3.81	4.22	4.61	4.99	5.35	2.64	[illegible]	3.66	4.07	4.46	[illegible]	5 20	2 59	3.14	3 61	4 02	4 41	[illegible]	5 15
600	30	2.80	3.35	3.81	4 22	4.61	4.98	5.34	2.62	[illegible]	3.63	4.04	4.43	4 80	5.16	2 56	3 11	3 56	3.98	4 37	4 74	5 10
600	35	2.83	3.37	3.83	4 24	4.63	5.00	5.36	2 61	3.15	3 60	4 01	4.40	4.77	5 13	2 53	3 07	[illegible]	3 94	4 33	4 70	5 06
600	40	2.88	3 41	3 86	4.27	4 66	5.03	5.38	2 60	[illegible]	3.59	4.00	4.38	4 75	5 11	[illegible]	[illegible]	[illegible]	3 91	4.29	[illegible]	5 02

Table 6.--Operating costs using 81-117 BHP rubber-tired vehicles for three different stand densities commonly found in Montana, Idaho, and northwestern Wyoming

Distance (feet)	Slope (percent)	5 THOUSAND BOARD FEET PER ACRE							10 THOUSAND BOARD FEET PER ACRE							15 THOUSAND BOARD FEET PER ACRE						
		Logs/M bd.ft.							Logs/M bd.ft.							Logs/M bd.ft.						
		4	6	8	10	12	14	16	4	6	8	10	12	14	16	4	6	8	10	12	14	16
		Dollars/M bd ft.							*Dollars/M bd.ft.*							*Dollars/M bd.ft.*						
200	5	2 82	3.33	3.76	4.14	4.50	4.84	5.16	2.60	3.11	3.54	3.92	4.28	4.61	4.94	2.52	3.04	3.46	3.85	4.20	4.54	4.87
200	10	3.00	3.53	3.96	4.34	4.70	5.05	5.38	2.74	3.27	3.70	4.08	4.44	4.79	5.12	2.65	3.18	3.61	4.00	4.36	4.70	5.03
200	15	3.20	3.74	4.18	4.57	4.93	5.28	5.61	2.89	3.43	3.87	4.26	4.62	4.97	5.30	2.78	3.32	3.77	4.16	4.52	4.86	5.20
200	20	3.42	3.97	4.42	4.82	5.18	5.53	5.87	3.05	3.60	4.05	4.45	4.81	5.16	5.50	2.93	3.48	3.93	4.32	4.69	5.04	5.37
200	25	3 68	4.24	4.70	5.10	5.47	5.82	6.16	3.23	3.79	4.25	4.65	5.02	5.37	5.71	3.08	3.64	4.10	4.50	4.87	5.22	5.56
200	30	3.98	4.56	5.02	5.43	5.80	6.15	6.49	3.43	4.01	4.47	4.88	5.25	5.60	5.94	3.25	3.82	4.29	4.69	5.07	5.42	5.76
200	35	4.33	4.92	5.39	5.80	6.18	6.54	6.88	3.65	4.25	4.72	5.13	5.51	5.86	6.20	3.43	4.02	4.49	4.90	5.28	5.64	5.98
200	40	4.73	5.33	5.81	6.23	6.61	6.97	7.31	3.90	4.51	4.99	5.40	5.78	6.14	6.49	3.63	4.23	4.71	5.13	5.51	5.87	6.21
300	5	2.79	3.32	3.75	4.14	4.50	4.84	5.17	2.64	3.17	3.60	3.99	4.35	4.69	5.02	2.59	3.12	3.55	3.94	4.30	4.64	4.97
300	10	2 94	3.48	3.92	4.31	4.68	5.02	5.36	2.76	3.31	3.75	4.14	4.50	4.85	5.18	2.71	3.25	3.69	4.08	4.45	4.79	5.12
300	15	3 10	3 66	4.11	4.51	4.87	5.22	5.56	2.90	3.45	3.90	4.30	4.67	5.01	5.35	2.83	3.38	3.83	4.23	4.60	4.95	5.28
300	20	3.29	3.86	4.31	4.71	5.08	5.44	5.77	3.04	3.61	4.07	4.47	4.84	5.19	5.53	2.96	3.53	3.98	4.38	4.75	5.11	5.44
300	25	3.49	4.07	4.54	4.95	5.32	5.67	6 01	3.19	3.77	4.24	4.65	5.02	5.37	5.71	3.09	3.67	4.14	4.55	4.92	5.27	5.61
300	30	3.73	4.32	4.79	5.20	5.58	5.94	6.28	3.36	3.95	4.43	4.84	5.22	5.57	5.91	3.24	3.83	4.30	4.72	5.09	5.45	5.79
300	35	3.99	4.60	5.08	5.50	5.88	6.24	6.58	3.54	4.15	4.63	5.05	5.43	5.79	6.13	3.39	4.00	4.48	4.90	5.28	5.64	5.98
300	40	4.29	4.91	5.40	5.82	6.21	6.57	6.91	3.74	4.36	4.85	5.27	5.66	6.02	6.36	3.56	4.18	4.67	5.09	5.47	5.84	6.18
400	5	2.83	3.37	3.81	4.21	4.57	4.92	5.25	2.72	3.26	3.70	4.10	4.46	4.81	5.14	2.68	3.22	3.67	4.06	4.42	4.77	5.10
400	10	2.97	3.52	3.97	4.37	4.74	5.09	5.42	2.84	3.39	3.84	4.24	4.61	4.96	5.29	2.79	3.35	3.80	4.20	4.57	4.91	5.25
400	15	3.12	3.69	4.14	4 55	4.92	5.27	5.61	2.96	3.53	3.99	4.39	4.76	5.11	5.45	2.91	3.48	3.94	4.34	4.71	5.06	5.40
400	20	3.28	3.86	4.33	4.73	5.11	5.46	5.80	3.09	3.68	4.14	4.55	4.92	5.28	5.62	3.03	3.61	4.08	4.49	4.86	5.21	5.55
400	25	3.46	4.05	4.53	4.94	5.32	5.67	6.02	3.23	3.83	4.30	4.71	5.09	5.45	5.79	3.16	3.75	4.23	4.64	5.02	5.37	5.72
400	30	3.66	4.27	4.75	5.17	5.55	5.91	6.25	3.38	3.99	4.47	4.89	5.27	5.63	5.97	3.29	3.90	4.38	4.80	5.18	5.54	5.88
400	35	3.88	4.50	4.99	5.42	5.80	6.16	6.51	3.55	4.17	4.66	5.08	5.46	5.83	6.17	3.43	4.05	4.54	4.97	5.35	5.71	6.06
400	40	4.13	4.77	5.26	5.69	6 08	6.44	6.79	3.72	4.36	4.85	5.28	5.67	6.03	6.38	3.59	4.22	4.71	5.14	5.53	5.89	6.24
500	5	2.90	3.46	3.91	4.31	4.67	5.02	5.36	2.81	3.37	3.82	4.22	4.59	4.93	5.27	2.78	3.34	3.79	4.19	4.56	4.90	5.24
500	10	3.03	3.60	4.06	4.46	4.83	5.19	5.52	2.93	3.50	3.96	4.36	4.73	5.08	5.42	2.89	3.46	3.92	4.32	4.70	5.05	5.38
500	15	3.17	3.75	4.22	4.63	5.00	5.36	5.70	3.05	3.63	4.10	4.50	4.88	5.23	5.57	3.00	3.59	4.06	4.46	4.84	5.19	5.53
500	20	3.32	3.92	4.39	4.80	5.18	5.54	5.88	3.17	3.77	4.24	4.66	5.03	5.39	5.73	3.12	3.72	4.19	4.61	4.98	5.34	5.68
500	25	3.48	4.09	4.57	4.99	5.37	5.73	6.08	3.30	3.91	4.39	4.81	5.20	5.55	5.90	3.24	3.85	4.33	4.75	5.14	5.49	5.84
500	30	3.66	4.29	4.78	5.20	5.58	5.95	6.29	3.44	4 07	4.56	4.98	5.36	5.73	6.07	3.37	3.99	4.48	4.91	5.29	5.65	6.00
500	35	3.86	4.50	5.00	5 42	5.81	6.18	6.53	3.59	4.23	4.73	5.15	5.54	5.91	6.26	3.50	4.14	4.64	5.06	5.45	5.82	6.17
500	40	4 08	4.73	5.24	5.67	6.06	6.43	6.78	3.75	4.40	4.91	5.34	5.73	6.10	6.45	3.65	4.29	4.80	5.23	5.62	5.99	6.34
600	5	2.98	3.56	4.02	4.42	4.79	5.14	5.48	2.91	3.48	3.94	4.35	4.72	5.07	5.41	2.88	3.46	3.92	4.32	4.69	5.05	5.38
600	10	3.11	3.70	4.16	4.57	4.95	5.30	5.64	3.02	3.61	4.08	4.49	4.86	5.22	5.56	2.99	3.58	4.05	4.46	4.83	5.19	5.53
600	15	3.24	3.84	4.32	4.73	5.11	5.47	5.81	3.14	3.74	4.21	4.63	5.01	5.36	5.71	3.11	3.70	4.18	4.59	4.97	5.33	5.67
600	20	3.38	4.00	4.48	4.90	5.28	5.64	5.98	3.26	3.87	4.36	4.77	5.16	5.52	5.86	3.22	3.83	4.31	4.73	5.12	5.48	5.82
600	25	3.54	4.16	4.65	5.08	5.46	5.83	6.17	3.39	4.01	4.50	4.93	5.31	5.68	6.02	3.34	3.96	4.45	4.88	5.26	5.63	5.97
600	30	3.71	4.34	4.84	5.27	5.66	6.02	6.37	3.52	4.16	4.66	5.09	5.48	5.84	6.19	3.46	4.10	4.60	5.02	5.41	5.78	6.13
600	35	3.89	4.54	5.04	5.48	5.87	6.24	6 59	3.66	4.31	4.82	5.25	5.65	6.01	6.37	3.59	4.24	4.74	5.18	5.57	5.94	6.29
600	40	4.09	4.75	5 26	5.70	6.10	6.47	6.82	3.81	4.48	4.99	5.43	5.83	6.20	6.55	3.72	4.38	4.90	5.34	5.73	6.10	6.46

Schillings, Paul L.

1969. A technique for comparing the costs of skidding methods. U.S. Dep. Agr., Forest Serv., Intermountain Forest and Range Exp. Sta., Ogden, Utah 84401. 23 pp., illus. (USDA Forest Serv. Res. Pap. INT-60)

A series of tables shows costs of skidding as determined by various types of equipment, distances for skidding, percent of slope, logs per MBF, and MBF per acre. By consulting these tables a contractor can compare methods of skidding according to their relative operating costs and thus estimate costs for his own operation. Such cost estimates must be regarded as tentative and subject to revision.

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Table 9.--Operating costs using shovels (tongs) for three different stand densities commonly found in Montana, Idaho, and northwestern Wyoming

Distance (feet)	Slope (percent)	5 THOUSAND BOARD FEET PER ACRE							10 THOUSAND BOARD FEET PER ACRE							15 THOUSAND BOARD FEET PER ACRE						
		Logs/M bd.ft.							Logs/M bd.ft.							Logs/M bd.ft.						
		4	6	8	10	12	14	16	4	6	8	10	12	14	16	4	6	8	10	12	14	16
		Dollars/M bd ft							*Dollars/M bd ft*							*Dollars/M bd ft*						
25	5	5 82	6 22	6.63	7 03	7.44	7.84	8 25	3.31	7.2	4.12	4.53	4 93	5.34	5.75	2 48	2 88	3 29	3 69	4 10	4 50	4.91
25	10	6 34	6 69	7.04	7 40	7.75	8.10	8.46	3.52	[illegible]	4.23	4 58	4.93	5 29	5 64	2 58	2.93	3.29	3 64	4 00	[illegible]	4.70
25	15	7 02	7 32	7.62	7 92	8.22	8.52	8.83	3.81	4 11	4.41	4.71	5.01	5.32	5 62	2 74	3.04	3.34	3 64	3 95	4 25	4 55
25	20	7 90	8 15	8 40	8 65	8.90	9.15	9.40	4 20	[illegible]	4.70	4.95	5 20	5 45	5.70	2 96	3.21	3.46	3.71	3.96	4.21	4.46
25	25	9 06	9 26	9 46	9 66	9 85	10 05	10.25	4.73	[illegible]	5.12	5.32	5 52	5.72	5 92	3 28	3.48	3.68	3 88	4 07	4 27	4.47
25	30	10 56	10 71	10 85	11.00	11.14	11.29	11.44	5.42	[illegible]	5.72	5.86	6.01	6.15	6.30	3.71	3 86	4.00	4 15	4.30	4.44	[illegible]
25	35	12 45	12 55	12 64	12 74	12.83	12.92	13.02	6.32	[illegible]	6.51	6.60	6.70	6 79	6 88	4 27	4 37	4.46	4 56	[illegible]	4 75	4.84
25	40	14 73	14 77	14.82	14 86	14.90	14.94	14.99	7.41	7 45	7.49	7.53	7 58	7 62	7 66	4.96	5 01	5.05	5.09	5.13	5 18	5 22
50	5	3 52	4 03	4.54	5 05	5.56	6.07	6.58	2.27	2 78	3.29	3.80	4.31	4.82	5.33	1 85	2 36	2 87	3 38	3.89	4.40	4 91
50	10	3 73	4 19	4 64	5.10	5.56	6.02	6.48	2.32	[illegible]	3.24	3 69	4.15	4 61	5.07	1.85	2.31	2 77	3 22	3 68	4 14	4 60
50	15	4 02	4 42	4.83	5 23	5.64	6.05	6.45	2.41	[illegible]	3.22	3.63	4 04	4.44	4 85	1 88	2.28	2.69	3.10	[illegible]	3 91	4 31
50	20	4.41	4 76	5 12	5 47	5.83	6.18	6 53	2.56	2 91	3.26	3.62	3 97	4.33	4 68	1 94	2 29	2 65	3 00	3 36	3.71	4 06
50	25	4 94	5 24	5 54	5 84	6.15	6.45	6 75	2.77	3 07	3.37	3.68	3.98	4.28	4.58	2 05	2 35	2 65	2 95	3 25	3 56	3 86
50	30	5 63	5 88	6 13	6 38	6.63	6.89	7.14	3.06	[illegible]	3.57	3.82	4.07	4.32	4 57	2 21	2.46	2.71	2 96	3 21	3 46	3 71
50	35	6 53	6 73	6.92	7 12	7.32	7.52	7.72	3.46	[illegible]	3.86	4.06	4 25	4.45	4.65	2 44	2.64	2.83	3 03	3 23	3 43	3.63
50	40	7 61	7 76	7 91	8 06	8.20	8.35	8 50	3.95	[illegible]	4 25	4.39	4.54	4.69	4.83	2 73	2.88	3 02	3 17	3.32	3.47	[illegible]
75	5	2 89	3 51	4 12	4 74	5.35	5.97	6.58	2 06	2 67	3.29	3.90	4.52	5.13	5 74	1 78	2 39	3.01	3 62	4.24	4 85	5 47
75	10	3 00	3 56	4 12	4 68	5 25	5.81	6.37	2.06	2 62	3.18	3.75	4.31	4 87	5.43	1 75	2 31	2 87	[illegible]	4 00	4 56	5.12
75	15	3 16	3 67	4 18	4 69	5.20	5.71	6.22	2.09	2 60	3.11	3.62	4 13	4 64	5.15	1 73	2 24	2.75	3 26	3 77	4 28	4 79
75	20	3 38	3 84	4 30	4 76	5.22	5.68	6.13	2.15	2 61	3.06	3 52	3.98	4 44	4.90	1 74	2.19	2 65	3.11	3.57	4 03	[illegible]
75	25	3 70	4 11	4 51	4 92	5.33	5.73	6.14	2 25	[illegible]	3.07	3.47	3.88	4 29	4 69	1 77	2 18	2 59	2 99	3 40	3 81	4.21
75	30	4 13	4 48	4 84	5 19	5.55	5 90	6.26	2.42	[illegible]	3.13	3.48	3 84	4.19	4 55	1.85	2 20	2 56	2 91	3 27	3 62	3 98
75	35	4 69	4 99	5 30	5 60	5.90	6.21	6.51	2.65	2 95	3.25	3.56	3 86	4.16	4 46	1 96	2 27	[illegible]	2 87	3.18	3 48	3 78
75	40	5 38	5.63	5 88	6 14	6.39	6 64	6.89	2 94	3 19	3.44	3 69	3 94	4 20	4.45	2.13	2 38	2 63	2 88	3 13	3.38	3 63
100	5	2 68	3 40	4 12	4 84	5 56	6.28	7.00	2 06	[illegible]	3.50	4.21	4.93	5.65	6.37	1.85	2 57	3 29	4.01	4.72	5.44	6.16
100	10	2 74	3 40	4 07	4 74	5 40	6.07	6 74	2.03	[illegible]	3.37	4.03	4.70	5.37	6 03	1.80	2 46	3.13	3 80	4 46	[illegible]	5 80
100	15	2 83	3 44	4 06	4 67	5.29	5.90	6.52	2.03	[illegible]	3.26	3.87	4 49	5.10	5 72	1.76	2 37	2.99	[illegible]	4 22	4.83	5 45
100	20	2 97	3 54	4 10	4 66	5.23	5.79	6.35	2 05	2 61	3.17	3.74	4.30	4.86	5.43	1.74	2 30	2 86	3.43	3 99	4 55	5 12
100	25	3 18	3 70	4 21	4 72	5.23	5.74	6.25	2.10	[illegible]	3.12	3.63	4.15	4 66	5.17	1.74	2 25	2 76	3.27	3 78	4 30	4.81
100	30	3 48	3 94	4 40	4 86	5.32	5.78	6.24	2.20	2 66	3.12	3.58	4 03	4.49	4.95	1 77	2 23	2 69	3.15	3 61	4.07	4.53
100	35	3 88	4 28	4.69	5 10	5.51	5.91	6.32	2.34	2 75	3.16	3.57	3.97	4.38	4.79	1.83	2 24	2 65	3 05	3 46	3 87	4.28
100	40	4 37	4 72	5 08	5 44	5.79	6 15	6 50	2.54	[illegible]	3 25	3.60	3 96	4.32	4 67	1 93	2.28	2 64	2 99	3.35	3 70	4 06
125	5	2 64	3.47	4.29	5 11	5.93	6.76	7 58	2.14	[illegible]	3.79	4 61	5.43	6 26	7.08	1 97	2 80	3 62	4 44	5 27	6 09	6 91
125	10	2 66	3 43	4 21	4 98	5 75	6.52	7.29	2.10	[illegible]	3 64	4.41	5.18	5 96	6 73	1 91	2 68	3.45	4 23	5 00	5 77	6.54
125	15	2 72	3.44	4.16	4 87	5.59	6.31	7 03	2 08	[illegible]	3 51	4.23	4.95	5 67	6 39	1 86	2 58	3.30	4 02	4 74	5 46	6.18
125	20	2 81	3 48	4 15	4 81	5.48	6.15	6.82	2.07	[illegible]	3 41	4 07	4.74	5 41	6 07	1 82	2 49	3.16	3 83	4 49	5 16	5 83
125	25	2 96	3 58	4.19	4 81	5.42	6.04	6 65	2.09	2 71	3.32	3.94	4.55	5.17	5 79	1 80	2 42	3 03	3 65	4.27	4 88	5.50
125	30	3 18	3 74	4.30	4 87	5.43	5 99	6.56	2.15	2 71	3 28	3.84	4.40	[illegible]	5 53	1 81	2 37	2 93	3 50	4 06	4 62	5.19
125	35	3 47	3 98	4 50	5 01	5 52	6.03	6.54	2.25	[illegible]	3.27	3.78	4.29	4.80	5 32	1 84	2 35	2 86	3 37	3 88	4 40	4 91
125	40	3 85	4 31	4 76	5 22	5 68	6.14	6.60	2 38	[illegible]	3.30	3.76	4 22	4.68	5.14	1.89	2 35	2 81	3 27	3 73	4.19	4.65

Headquarters of the Intermountain
Range Experiment Station are in Ogden, Utah.
Field Research Work Units are maintained in:

Boise, Idaho
Bozeman, Montana (in cooperation with
Montana State University)
Logan, Utah (in cooperation with Utah
State University)
Missoula, Montana (in cooperation with
University of Montana)
Moscow, Idaho (in cooperation with the
University of Idaho)
Provo, Utah (in cooperation with
Brigham Young University)

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The Forest Service of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing nation.